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ROYAL AERONAUTICAL SOCIETY 1866

Journal

of

THE ROYAL AERONAUTICAL SOCIETY

MARCH 1956

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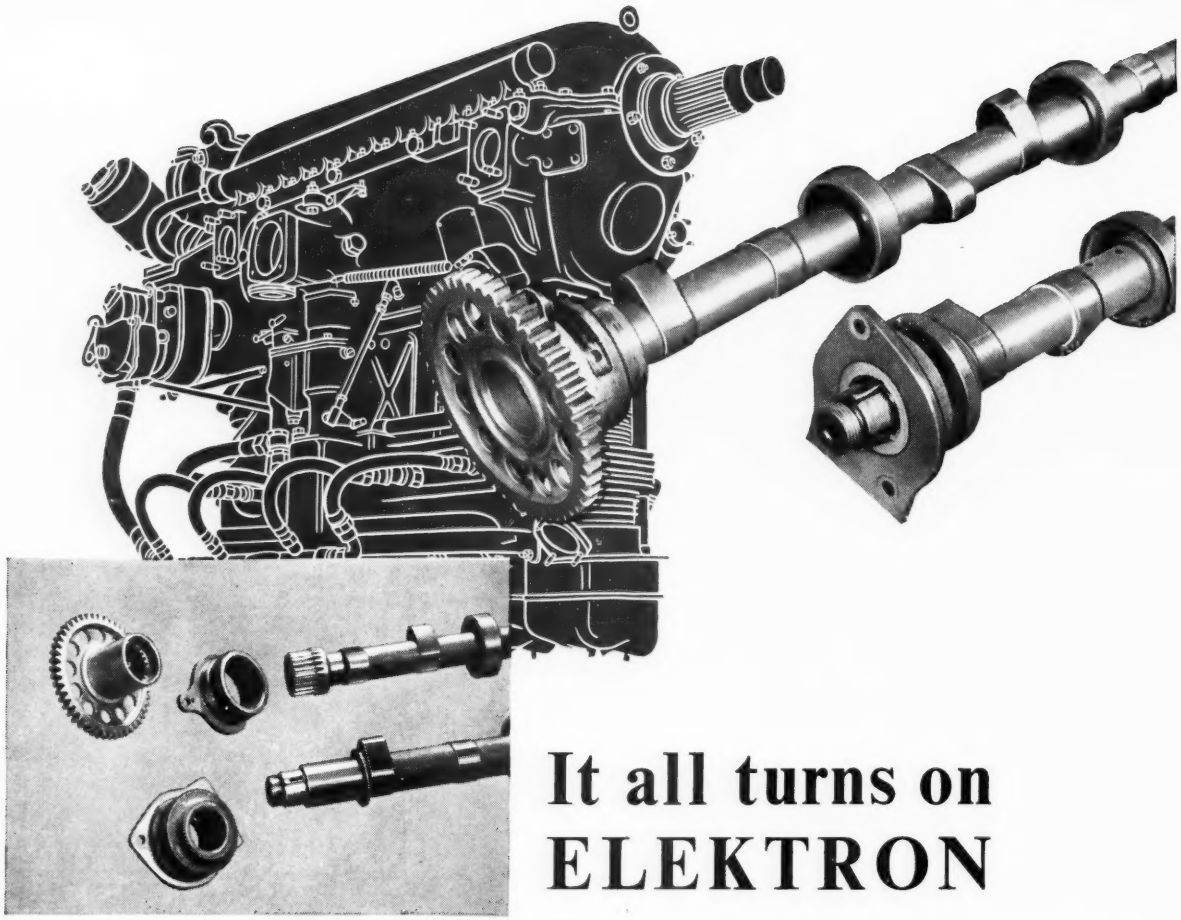

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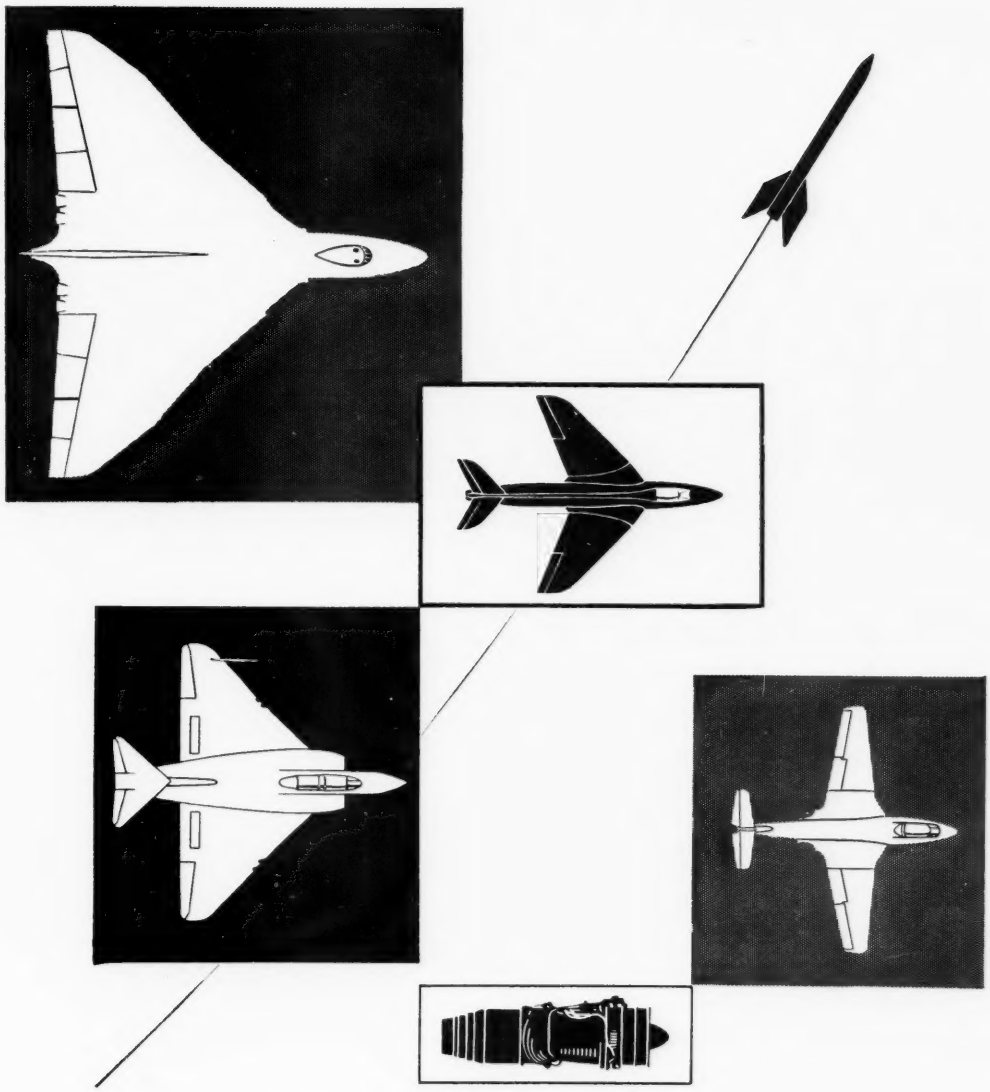

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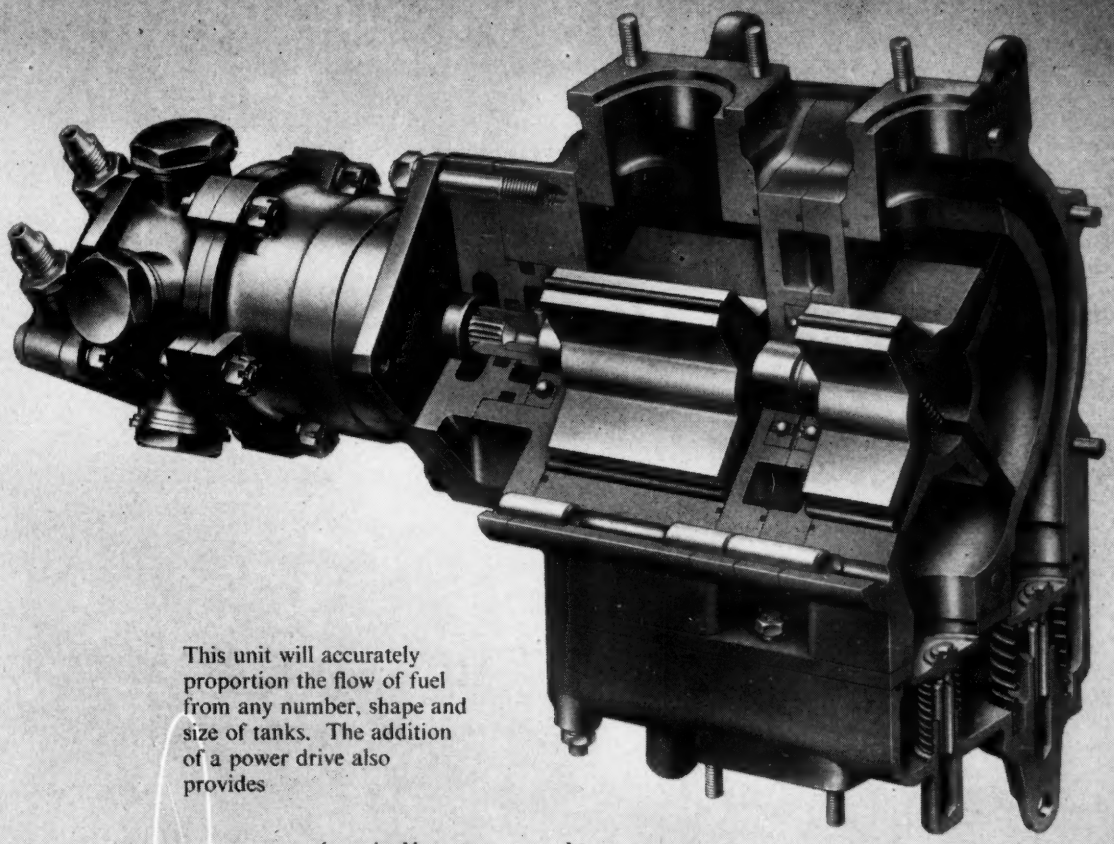

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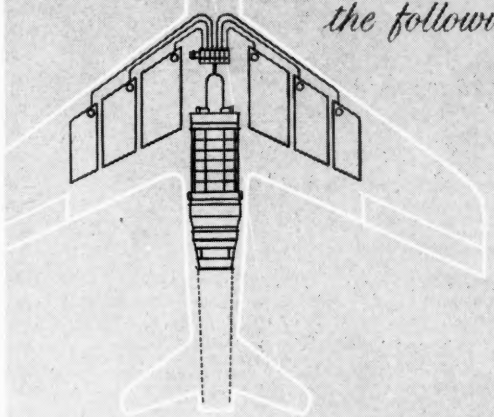

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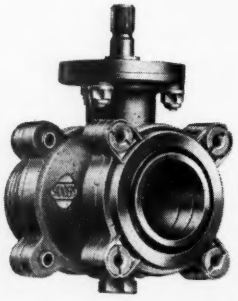

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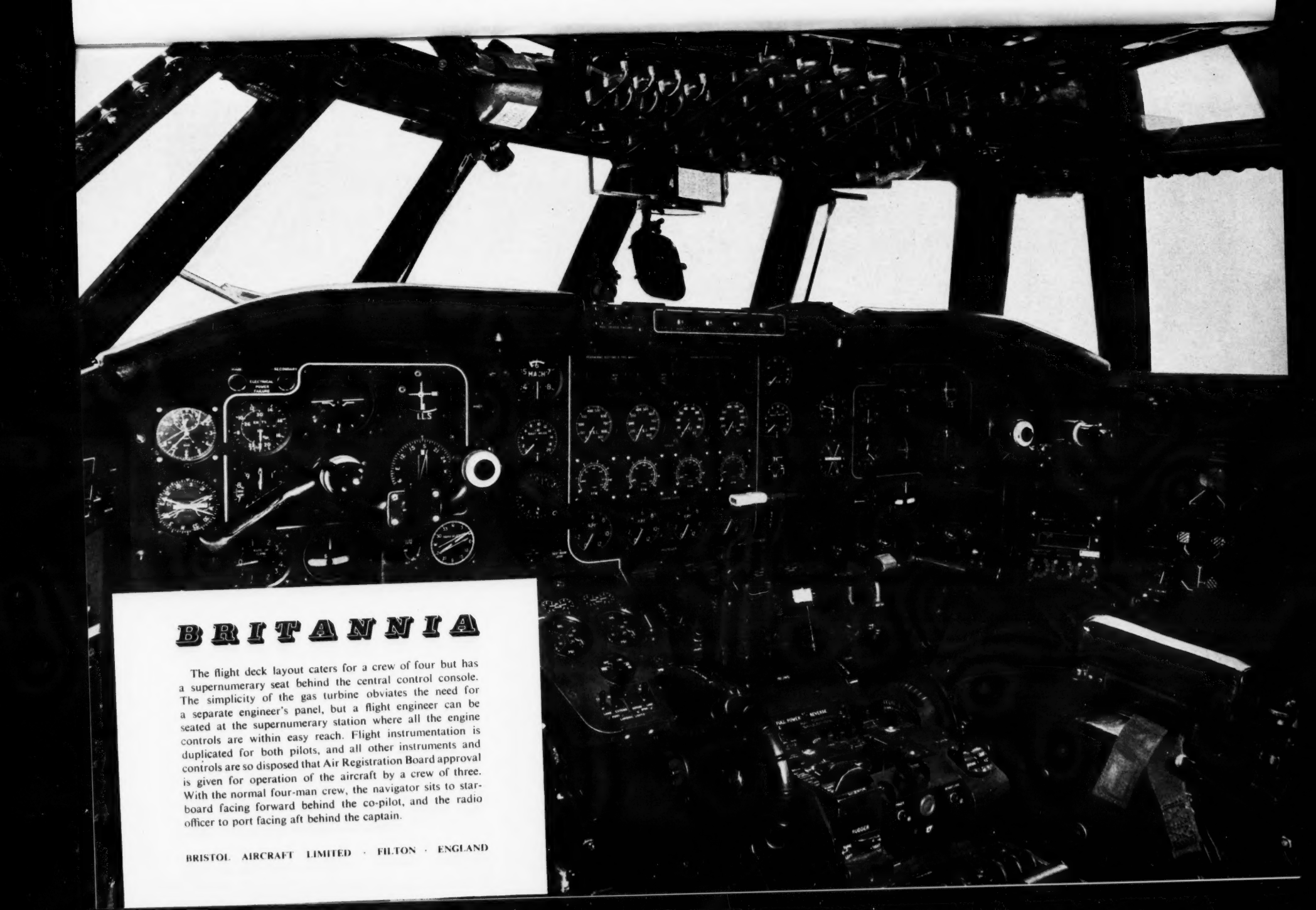

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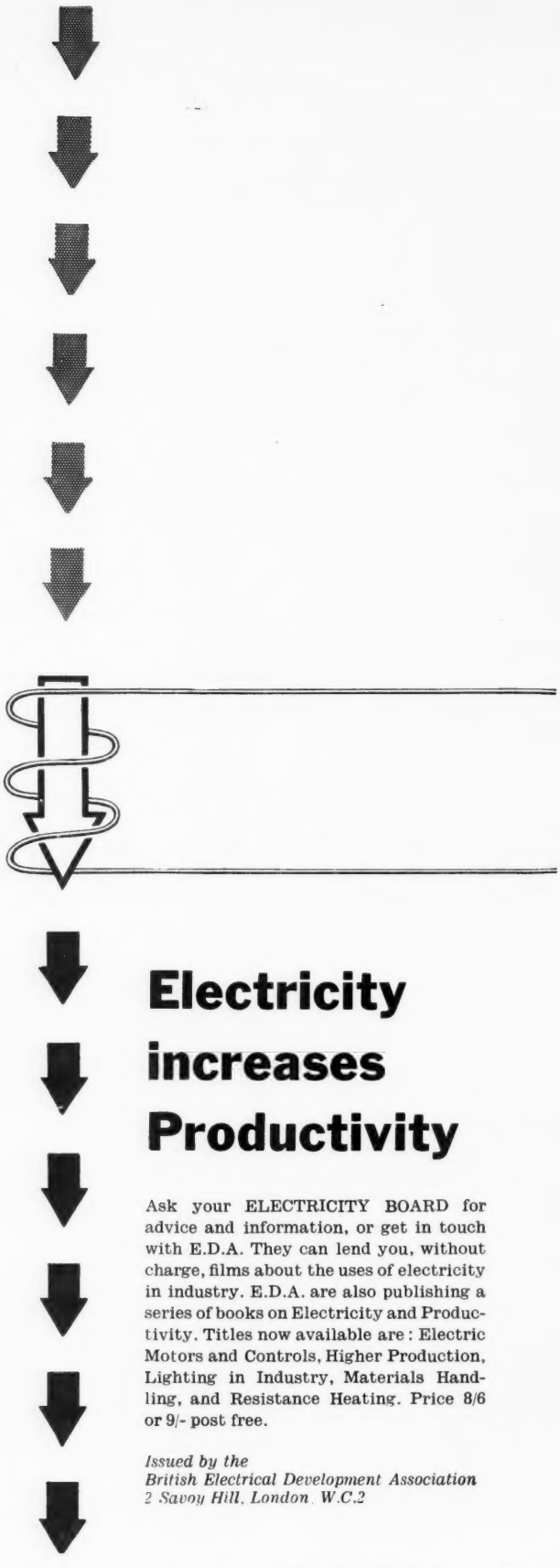

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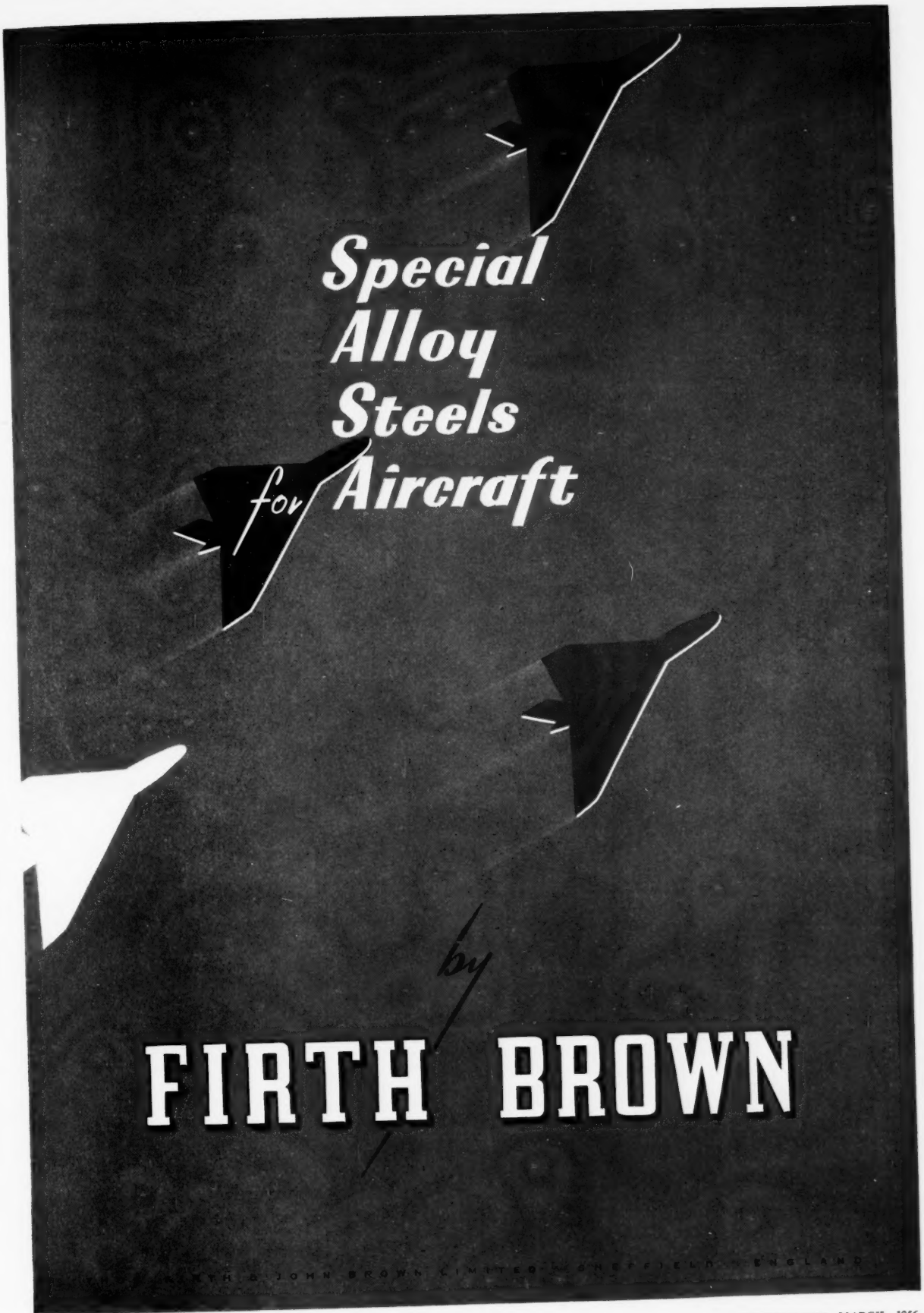
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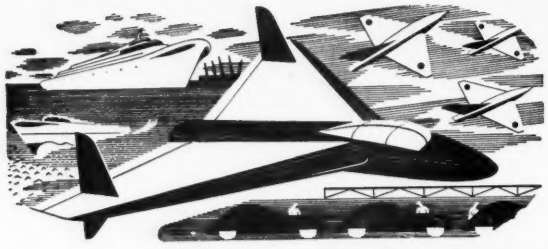

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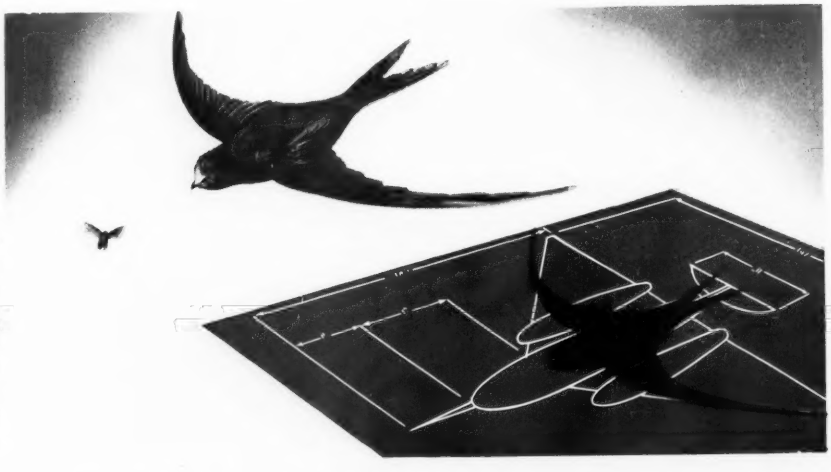

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ADDITIONS TO THE LIBRARY. REPORTS.

All communications for publication in, and advertisements for, the JOURNAL *should be addressed to the Editor,* JOAN BRADBROOKE, *A.R.Ae.S.; all communications on general matters affecting the Society should be addressed to the Secretary,* A. M. BALLANTYNE, *T.D., B.Sc., Ph.D., Hon.F.C.A.I., A.F.I.A.S., A.F.R.Ae.S.*

None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless otherwise stated.

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NOTICES

An annual sum of £250 is available for premium awards for papers, including Technical Notes, published in the Journal. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics

Nomination of Candidates for Council

The following is an extract from the By-Laws:—

"The Twenty-one ordinary members (of the Council) shall be nominated and elected from among the members of the Society. At the date of their election at least ten shall be Fellows, and one at least shall be in each of the following classes: Associate Fellow, Associate and Graduate.

"Of the ordinary members of the Council, that number necessary to create seven vacancies shall retire annually. The retiring members shall be those with the longest service since their last election but they shall be eligible for re-election.

"Nominations of candidates for election to the Council must be received by the Secretary not later than 10th April in each year and shall include statements in writing by the candidates that they are willing to serve. The nomination forms shall be signed by one proposer and two seconders, all of whom shall be Voters."

Nomination forms may be obtained on application to the Secretary.

Annual General Meeting, 10th May, 1956

Notice is hereby given that the Annual General Meeting of the Royal Aeronautical Society, with which is incorporated the Institution of Aeronautical Engineers, will be held on Thursday, 10th May at 5.30 p.m. in the offices of the Society, 4 Hamilton Place, London, W.1.

Agenda

1. To read the Notice convening the Meeting.
2. To receive and deliberate upon the Report of the Council on the state of the Society and the Balance Sheets and Income and Expenditure Accounts of The Royal Aeronautical Society and Aeronautical Trusts Limited for the year ended 31st December, 1955.
3. To receive the names of those elected to Council for the years 1956-1959.
4. To announce the names of Fellows elected by the Council in accordance with By-Law 4.
5. To elect the Auditors for the year 1956.
6. Any other business.

By Order of the Council
A. M. BALLANTYNE
Secretary

NOTE:—In accordance with the By-Laws any member whose subscription has not been paid before the first day of April is not entitled to vote.

Light refreshments will be served after the meeting.

Graduates' and Students' Section—Visits

A visit has been arranged to the Fairey Aviation Company's works at Hayes for Saturday, 17th March 1956.

A visit has also been arranged to the Royal Air Force Station at West Malling, near Maidstone, for Saturday 7th April 1956. This visit has been granted because the Section was unable to visit them last September. West Malling is an operational Fighter Station within easy reach of London. Applications for these visits should be made as soon as possible to the Hon. Visits Secretary, N. K. Benson, 14 Wakering Road, Barking, Essex.

Easter 1956

The Library and the offices of the Society will be closed for the Easter holiday from 5 p.m. on Thursday 29th March until 9 a.m. on Tuesday 3rd April 1956.

Addition to New Year Honours List

Group Captain G. Thripp (Associate Fellow) has been created an Officer of the Most Excellent Order of the British Empire (Civil Division).

Institute of the Aeronautical Sciences

Dr. Edward R. Sharp, Director of the Lewis Flight Propulsion Laboratory, N.A.C.A., has been elected President of the Institute of the Aeronautical Sciences for 1956 in succession to Mr. Robert Gross who retired on 23rd January 1956.

Elliott Memorial Prize

The Elliott Memorial Prize has been awarded to Flight Sergeant Apprentice J. J. McMahon of the April 1953 Entry at R.A.F. Halton, who obtained the highest marks in the General Studies Examination. It will be presented to him at the Graduation Prize Giving on 28th March 1956.

E. J. N. Archbold Memorial Prize 1955

The E. J. N. Archbold Memorial Prize for 1955 has been awarded to John Timothy Greenslade, a student apprentice at the Royal Aircraft Establishment Technical College, Farnborough.

Royal Aeronautical Society Prize in Aeronautics 1955

The Royal Aeronautical Society Prize in Aeronautics for 1955 has been awarded to A. J. Sarnecki who is studying at Cambridge University.

Royal Aeronautical Society Educational Fund

A grant of £50 from the Society's Educational Fund has been awarded to A. L. Knight to enable him to continue his course at the University of Bristol for the degree of B.Sc. in Engineering (Aeronautical).

Fifth World Power Conference

The Fifth World Power Conference will be held in Vienna from 17th-23rd June 1956. Copies of the Programme can be obtained from: The Secretary, British National Committee, World Power Conference, 201 Grand Buildings, Trafalgar Square, London, W.C.2. Membership is open to all persons possessing appropriate professional qualifications or occupying responsible posts in the British fuel and power and related industries (including "user" industries).

Acknowledgments

The Council acknowledge with grateful thanks some interesting historical photographs, admission tickets and a copy of the first Aerial Derby programme of 1912 from Mrs. John Rhodes, whose husband was an early associate of Robert Blackburn.

They also wish to thank Mr. G. Vidler, of Crawford Street, W.1, for the gift of five large framed photographs of historical aircraft (c. 1910), and the Editor of "Engineering" for forty-seven volumes of *Bulletin de l'association technique maritime et aeronautique.*

DIARY

LONDON

15th March

MAIN LECTURE.—The High Temperature Turbo-Jet Engine. D. G. Ainley. The Institution of Civil Engineers, Gt. George Street, London, S.W.1. 6 p.m. (Tea 5.30 p.m.)

20th March

SECTION LECTURE.—Experiments on Flow Over Swept-Back Wings. P. T. Fink. The Library, 4 Hamilton Place. 7 p.m.

21st March

Main Lecture at Manchester Branch.—THE FIRST CHADWICK MEMORIAL LECTURE. The Life and Work of Roy Chadwick. H. Rogerson, M.B.E. Reynolds Hall, College of Technology, Manchester. 7.30 p.m.

27th March

SECTION LECTURE.—**CANCELLED**—The Rise of The Aircraft in Pest Control Agriculture, J. E. Harper, has been cancelled.

5th April

Main Lecture at Belfast Branch.—Problems Associated with the Production and Use of Modern Light Aluminium Alloys. G. Forrest and K. Gunn. Central Hall, Belfast College of Technology. 7 p.m.

12th April

SECTION DISCUSSION.—Aircraft Interior Lay-out. Speakers will be:—Capt. O. P. Jones, R. C. Morgan, C. F. Holloway, D. P. Thorne and a B.O.A.C. Stewardess. The Library, 4 Hamilton Place, London, W.1. 7 p.m.

17th April

SECTION LECTURE.—Investigation of Aircraft Accidents. E. L. Ripley, O.B.E. The Library, 4 Hamilton Place, London, W.1. 7 p.m.

19th April

MAIN LECTURE.—**High Speed Experimntal Test Flying. Lt.-Col. Charles E. Yeager, U.S.A.F. The Institution of Civil Engineers, Gt. George Street, London, S.W.1. 6 p.m. (Tea 5.30 p.m.).**

24th April

SECTION LECTURE.—The Development of Helicopter Transport. R. H. Whitby. The Library, 4 Hamilton Place, London, W.1. 7 p.m.

GRADUATES' AND STUDENTS' SECTION

17th March

Visit to Fairey Aviation Company, Hayes.

28th March

Artificial Space Satellites. A. V. Cleaver. The Library, 4 Hamilton Place, London, W.1. 7.30 p.m.

7th April

Visit to R.A.F. West Malling.

18th April

Gas Turbines—Propeller or Jet? R. M. Fitzgerald. The Library, 4 Hamilton Place, London, W.1. 7.30 p.m.

BRANCHES

12th March

Halton.—Paper by a Junior Member. Branch Hut, R.A.F., Halton. 6.45 p.m.

Henlow.—The Domain of the Helicopter. R. Hafner. Building No. 62, R.A.F. Technical College. 7.30 p.m.

14th March

Southampton.—CANCELLED—Airframe Fatigue, W. Tye, has been cancelled.

Weybridge.—The Control of Welding Processes in Aircraft Production. H. E. Dixon. (Combined Meeting with South London Branch of Institute of Welding). Vickers-Armstrongs (Aircraft) Ltd., Weybridge. 6 p.m.

16th March

Birmingham.—Aircraft Wheels and Brakes. Development and Testing. P. W. Dryland. The Goodyear Tyre & Rubber Co. Ltd., Wolverhampton. 7.30 p.m.

19th March

Halton.—Aerial Surveys. H. G. Dawe. Branch Hut, R.A.F., Halton. 6.45 p.m.

20th March

Belfast.—Radio Aids to Navigation. H. H. Capes. Kerr Room, Kensington Hotel, Belfast. 7 p.m.

21st March

Chester.—Joint Meeting with Stanlow Branch of Institute of Petroleum. Fuels and Lubricants for Jet Engines. K. C. Hunt. The Grosvenor Hotel, Chester. 7.30 p.m.

Coventry.—Some Problems of Helicopter Design and Operation. D. M. Davies. The Wine Lodge, Coventry. 7.30 p.m.

Gloucester.—Lecture. The Wheatstone Hall, Brunswick Road, Gloucester. 7.30 p.m.

Manchester.—MAIN LECTURE. The First Chadwick Memorial Lecture: The Life and Work of Roy Chadwick. H. Rogerson, M.B.E. Reynolds Hall, College of Technology, Manchester. 7.30 p.m.

Preston.—The Advantages and Disadvantages of Swept Wings. Dr. D. Küchemann. Queen's Hotel, Lytham. 7.30 p.m.

Reading and District.—Some Maintenance Aspects of Viscount Operation. E. R. Major. Western Manufacturing Ltd. Canteen, Reading. 6 p.m.

22nd March

Isle of Wight.—Development of Gas Turbine Engines. Dr. S. G. Hooker, O.B.E. Clubhouse, Saunders-Roe Sports and Social Club, Church Path, E. Cowes. 6.30 p.m.

26th March

Henlow.—Film "We saw it happen." Building No. 62, R.A.F. Technical College, Henlow. 7.30 p.m.

27th March

Bristol.—The History and Application of Digital Computors. Dr. P. V. Bowden. Conference Room, Filton House, Bristol Aircraft Ltd. 6 p.m.

28th March

Southampton.—Film Show. Institute of Education, University of Southampton. 7 p.m.

2nd April

Derby.—The Possibilities of Atomic Energy for Aircraft Propulsion. J. E. B. Perkins. Rolls-Royce Welfare Hall, Nightingale Road, Derby. 6.15 p.m.

4th April

Brough.—Annual General Meeting. Lecture Hall, Yorkshire Electricity Board, Ferensway, Hull. 7.30 p.m.

Weybridge.—Glass for the Aircraft Industry. Dr. A. J. Holland. Vickers-Armstrongs (Aircraft) Ltd., Weybridge. 6 p.m.

5th April

Belfast.—MAIN LECTURE. Problems Associated with the Production and Use of Modern Light Aluminium Alloys. G. Forrest and K. Gunn. Central Hall, Belfast College of Technology. 7 p.m.

Isle of Wight.—Branch Prize Lectures. Clubhouse, Saunders-Roe Sports and Social Club, Church Path, E. Cowes. 6.30 p.m.

9th April

Halton.—Film "We saw it happen." Branch Hut, R.A.F., Halton. 6.45 p.m.

10th April

Boscombe Down.—Engine Development. Dr. S. G. Hooker, O.B.E. Lecture Hall, A. & A.E.E., Boscombe Down, Amesbury, Wilts. 5.45 p.m.

Bristol.—Titanium—A Survey. Major P. L. Teed. Conference Room, Filton House, Bristol Aircraft Ltd. 6 p.m.

11th April

Glasgow.—Film and Annual General Meeting. St. Enoch Hotel, Glasgow. 7.15 p.m.

13th April

Birmingham.—Prop-Jets in the Navy. W. H. Lindsey. Birmingham Engineering Centre, Stephenson Place. 7.30 p.m.

14th April

Southampton.—Annual Dance. The Refectory, University of Southampton. 8-12 p.m.

16th April

Halton.—Brains Trust on High Altitude Survival. Branch Hut, R.A.F., Halton. 6.45 p.m.

18th April

Coventry.—Annual General Meeting and Films. The Wine Lodge, Coventry. 7.30 p.m.

Preston.—Annual General Meeting and Film Show. R.A.F. Association, Preston. 7.30 p.m.

Southampton.—Full-Scale Layout. J. W. Earle (Joint Meeting with the Institute of Production Engineers, Southern Section). Institute of Education, University of Southampton. 7 p.m.

19th April

Cheltenham.—Annual General Meeting and Film "We saw it happen." St. Mary's College, Cheltenham. 7.30 p.m.

Reading and District.—Annual General Meeting and Film Show. G. R. Volkert. Western Manufacturing Ltd. Canteen, Reading. 6 p.m.

23rd April

Halton.—Film: From Touchdown to Take-off. Branch Hut, R.A.F., Halton. 6.45 p.m.

24th April

Belfast.—Annual General Meeting. Reception Room, Kensington Hotel, Belfast. 7 p.m.

26th April

Bristol.—Annual General Meeting and Film Show. Conference Room, Filton House, Bristol Aircraft Ltd. 6 p.m.

30th April

Halton.—Paper by a Junior Member. Branch Hut, R.A.F., Halton. 6.45 p.m.

Institute of Navigation—The Collision Problem

A meeting on "Relative Movement and the Collision Problem" will be held at the Royal Geographical Society, 1 Kensington Gore, London, S.W.7, on Wednesday 18th April 1956 at 5 p.m. (Tea at 4.30 p.m.). It will consist of an analysis by some members of the Technical Committee of the Institute of Navigation of the relevance of modern interception theory to the whole problem of collision in the air and at sea.

Annual Subsriptions

Members are reminded that their annual subscriptions became due on 1st January 1956. The rates are:—

	Home	Abroad
	£ s. d.	£ s. d.
Fellows	5 5 0	4 4 0
Associate Fellows	4 4 0	3 3 0
*Associates	3 3 0	3 3 0
Graduates (aged under 26)	2 2 0	2 2 0
Graduates (aged 26 and over)	2 12 6	2 12 6
Students (aged under 21)	1 1 0	1 1 0
Students (aged 21 and over)	1 11 6	1 11 6
Companions	3 3 0	3 3 0
Founder Members	2 2 0	2 2 0

* Any Associate elected before 1st October 1947 may, if he wishes, elect not to receive the Journal, and in this case his subscription will be reduced by £1 1s. 0d. to £2 2s. 0d.

It will avoid delay and confusion if members, when sending remittances for subscriptions, will state their names clearly and give their addresses and grades of membership. Remittances should be made payable to the Royal Aeronautical Society.

Elections

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

Lawrence Henry Berwick
Arne Rudolf Carlson
Michael John Cooke
Denis Cressey (*from Associate*)
Michael Joseph Cronin
John Ernest Felstead (*from Graduate*)
Newton David Hodgekiss (*from Graduate*)
Robert Frederick Hunt (*from Associate*)
Alan Powell (*from Graduate*)
Arthur Edward Rowland (*from Graduate*)
Joseph Charles Kent Sutton
Rupert Whitfield Traill-Nash (*from Graduate*)
Robert Longley Trillo (*from Graduate*)
William John Watkinson
Ronald Frederick West (*from Graduate*)
George Alan Whitfield

Associates

Uric Nathaniel Auguste
James Williams Carter
Wilfred Albert Haase
Frederick James Hill (*from Student*)
Bernard Towler

Graduates

Colin George Holdstock Abrahams (*from Student*)
Alan David Burgess
Trevor Charles Cox
Thomas James Cummings
Peter Stanley Deary
Olwyn Anthony D'Sylva (*from Student*)
Derek Ellington
Michael John Harris (*from Student*)
Harold Melville Kent (*from Student*)
Alan King
Frederick Dawson Calvin Mills
Ronald David Mills
Kevin Frank Rolph (*from Student*)
Colin Raymond Stephens
George Frederick William Stevens
Gerald David Turner

Students

Harishanker Sureshchandra Vallabhbhai Bhagat
Bihari Lal Dhar
Michael Richard Dominy
John Kenneth Harvey
Santosh Kumar Majumdar
Derek Leigh Marsden
Jerry Ohanes Melconian
Eric James Softley
Samuel George Sterling
Donald Stott
Colin Webb
Cyril James Whitehead

Companions

Ponniah Bala-Chandran
David Muir Mackie (*from Student*)
Sarva Daman Sahni

News of Members

R. M. Aldwinckle (*Associate Fellow*) has been appointed the Director of Instrument and Electrical Engineering, Air Force Headquarters, Ottawa.

E. S. Caro (*Associate*), Managing Director of Aerial Agriculture Ltd., and Engineering Alliance Ltd., and Director of Helicopter Services Ltd., has been elected President of the Aviation Industry Association of New Zealand (Inc.).

T. D. R. Carroll (*Associate Fellow*) has left B.O.A.C. where he was Senior Technical Officer (Aircraft) to become Assistant Design Manager (Britannia) with Bristol Aircraft Ltd.

E. B. Dove (*Associate Fellow*) has been appointed Chief Designer of Dowty Fuel Systems Ltd.

K. J. Dowell (*Associate*) has joined Smiths Aircraft Instruments as Senior Sales Representative dealing with Automatic Pilots, Flight Systems and Radio Navigation Systems.

J. P. Ford (*Associate*) formerly Managing Director of Brush Export Ltd. has been appointed Managing Director of Charles Colston Limited. He has also been appointed Chairman of Smith-Richards Limited and of Tallent (Aycliffe) Limited.

MAJOR J. VIVIAN HOLMAN (*Associate Fellow*) has recently been appointed Aeronautical Consultant to The General Fire Appliance Co. Ltd., New Addington, Surrey.

SIR BEN LOCKSPEISER (*Fellow*) retires from his post as Secretary to the Committee of the Privy Council for Scientific and Industrial Research on 10th March, 1956.

C. G. LONGFORD (*Associate Fellow*) is now Chief Flight Test Engineer at Gloster Aircraft Co. Ltd.

P. G. MASEFIELD (*Fellow*), Vice-President of the Society, has been elected an Honorary Fellow of the Institute of the Aeronautical Sciences.

P. R. MERSY (*Associate Fellow*) is now Resident Technical Officer for the Ministry of Supply at Sir W. G. Armstrong Whitworth Aircraft Ltd., Baginton.

J. C. OSBORNE (*Associate Fellow*) has been appointed Manager, Engine Accessories Sales, Accessories Division, Thompson Products, Inc., Cleveland 17, Ohio.

I. L. RYE (*Graduate*) has resigned his post as an Engineer III with the Ministry of Supply and took up a new post on 1st January, 1956 as a Section Leader in the Dynamics Group of the Structures Design Office at Bristol Aircraft Ltd., Filton.

SQUADRON LEADER J. G. TOLLEY (*Associate Fellow*) has been appointed Officer Commanding Servicing Squadron at Seletar, Singapore.

SQUADRON LEADER H. H. WATKINSON, R.A.F. (*Associate Fellow*) has taken up the appointment of ARM/G.W. at Headquarters, Fighter Command.

LIEUTENANT COMMANDER N. R. WHYATT (*Associate*), formerly Aviation Technical Officer at the Royal Insurance Co., is now Assistant Aircraft Surveyor at Lloyd's, Agency Department.

R. J. WICKENS (*Graduate*), formerly with the Patent Lightning Crusher Co., has now joined Mono Pumps Ltd., as a Research Engineer.

A. C. WILSON (*Associate*) and his firm have been appointed Design Consultants to the U.K. Atomic Energy Authority Headquarters, Risley.

JOURNAL BINDING

Permanent Binding

The new prices for permanent binding of Journals are:

1955 Volume (including packing and postage) £1 0s. 0d.

Previous Volumes (including packing and postage) .. .. £1 1s. 6d.

Journals, with a note of the name and address of the sender, should be sent direct to The Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the Offices of the Society.

Self-Binder Cases

Self-Binder cases of the "Easibind" type to hold 12 Journals (cost 11s. 6d. each) are available from the offices of the Society.

CHANGES OF ADDRESS OR APPOINTMENT

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address. He would also like to know of any change of appointment.

When notifying changes please give the following particulars:—

Name (in block letters). New address (in block letters).

Grade of Membership. Old address.

New appointment—Please give name and address of employer and position held.

Changes of address must be received *before the 15th of the month* in order to be effective for the JOURNAL for the following month.

The Journal of the Royal Aeronautical Society

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

VOLUME 60 MARCH 1956 NUMBER 543

PROFESSOR G. T. R. HILL, *Fellow*

1895 - 1955

WITH THE DEATH of Professor G. T. R. Hill, M.C., M.Sc., M.I.Mech.E., F.R.Ae.S., on 26th December 1955 the world of Aviation has lost one of the most lovable pioneers who ever breathed enthusiasm into flying.

Geoffrey Terence Rowland Hill was best known for his Pterodactyl tailless aircraft but his inventiveness did not stop with the Pterodactyls or even begin with them. His first recorded achievement in Aeronautics was to win a flying competition with a model aircraft which he had designed and built. He was then in his early teens and it was not long afterwards that he and his brother, who later became Air Chief Marshal Sir Roderic Hill, designed, built and flew a full scale glider. As a glider it was probably not a resounding success but as an enterprise by two boys in their teens in the year 1913, it was truly remarkable.

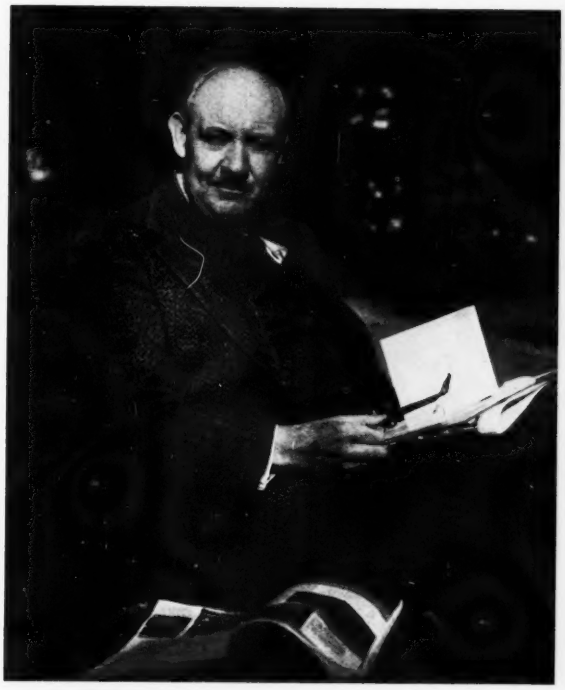
The difficulties which the two boys had to overcome were not only technical but also financial and, not surprisingly, parental. The technical problems were overcome by straight thinking and simple experiment. For example, the wing spars were stressed—or should we say proof loaded—by laying them across two chairs placed at roughly the semi-span of each wing and then the two brothers and, I think, two of their friends sitting astride the centre section and doing a little bouncing just to make sure.

The financial problems were solved largely by selling paintings by Roderic. Whenever funds were low Roderic had to stop work on the glider and paint some more pictures.

That they ever overcame the parental difficulties can only be attributed to the extraordinary persuasiveness which they both possessed throughout their lives.

Geoffrey was the first to fly the glider from a gentle slope on the South Downs near Eastbourne. Like all aircraft it took longer to prepare for flight than anyone expected and it was nearly dark when Geoffrey found himself airborne for the first time in his life in a glider which also had never flown before. A rather frightening phugoid motion soon developed in the midst of which Geoffrey suddenly heard the swish of grass under him and found that he had made a nearly perfect landing. Over the next 40 years Geoffrey looked back on that moment as the proudest in his life.

While all this was happening at weekends Geoffrey Hill was an undergraduate at University College, London, where he took his degree in 1914. He then



G. T. R. Hill.

entered the Royal Aircraft Factory as a graduate apprentice and remained there until 1916, when he obtained a commission in the Royal Flying Corps. It is ironical to reflect that he had previously been rejected as medically unfit for the Hampshire Air Parks Volunteers, a local unit formed by members of the Factory staff. He served in France with No. 29 Squadron until he nearly lost his life as the result of experimenting with an aircraft which had insufficient elevator power.

He was invalided home with the rank of captain and with the award of the M.C.

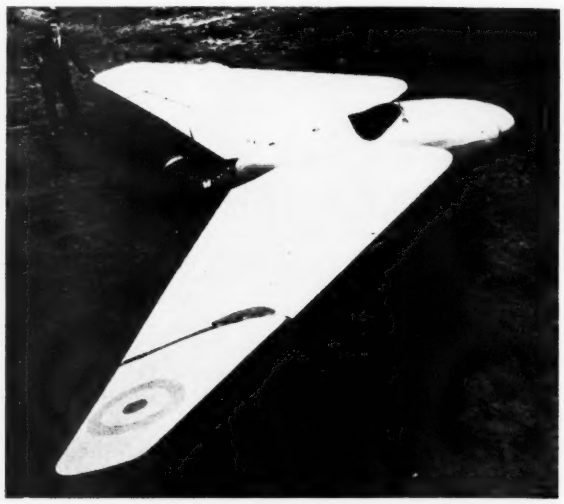
He then joined the Ministry headquarters as deputy to Mr. (later Professor Sir Leonard) Bairstow in control of aircraft research and experiment.

By 1918 he was in the air again, this time as Test Pilot in charge of the Aerodynamics Flight at Farnborough. Later he became Chief Test Pilot to Handley Page Limited where he shared in the early development

The original Hill Pterodactyl (32 h.p. Bristol Cherub engine) 1925.

of the Handley Page slat, undertaking both wind tunnel work and then full scale flight experiment on the DH.9 with a long undercarriage.

Throughout this time he had been profoundly concerned by the phenomenon of stalling and he set himself the task of designing a truly safe aeroplane. He made a close study of sea birds and came to the conclusion that they did not use their tails for longitudinal control in normal flight but relied on wing warping and changes of wing camber. This observation



The Westland-Hill Pterodactyl Mk. IA (75 h.p. Armstrong Siddeley Genet engine) 1926.

set him thinking along the lines which led him to his well known tailless pterodactyl configuration. He must also have been influenced by Dunne's work. Here his early experience with the glider came to his aid and, to test his new ideas, he again designed, built and flew a glider. This was in 1924 and the following year he fitted it with a Cherub engine—the Hill Pterodactyl Mk. 1, which now has its place in the Science Museum at South Kensington. During the time he developed this aircraft, Hill was the holder of an 1851 Exhibition Scholarship which involved experimental flying at the Royal Aircraft Establishment.

In 1926 Hill joined the staff of the Westland Aircraft Works and designed several further types of Pterodactyls, of which three were built. Among other novel features may be recorded the first use of wing sweepback variation during flight, use of spoiler air brakes, probably the first use of a bicycle type tandem-wheel undercarriage with wing tip skids and certainly the first use of wing tip slats on a swept-back wing. The Mk. IV was the first tailless aircraft ever to be spun, rolled and looped. The series culminated in the Mk. V in 1932, which was a two-seater sesquiplane fighter, powered by a Rolls-Royce Goshawk engine and capable of about 200 m.p.h. As it was built to an Air Ministry Specifica-

The Pterodactyl Mk. V two-seat fighter (600 h.p. Rolls-Royce Goshawk engine) 1932.

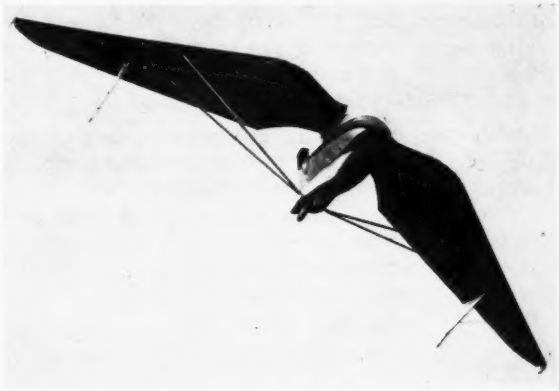
tion, the contract included among other things, the development of a power-operated gun turret. When the Pterodactyl was finally rejected in favour of a more conventional design Hill felt that the aircraft had been judged on the operation effectiveness of the gun turret and other extraneous things and that his ideas had never been assessed on their true worth. This was a great disappointment to him.

In 1934 Captain G. T. R. Hill was appointed to the Kennedy Chair of Mechanical Engineering at University College, London. It may well be that his most valuable work was done there because he was an inspiring lecturer, always able to instil enthusiasm into his students by his delightful style and happy wit and because he would go to enormous lengths to rig up all manner of practical demonstrations. He never tried to teach too much in any one lecture but made sure that what he did teach would be understood and remembered. There may be better ways of getting students through examinations, but Professor Hill was far more concerned that his students should leave him with the fundamental principles straight in their minds and with an enthusiasm for their work.

In the early part of the 1939-45 War Hill was in charge of the Air Defence Research Department of the R.A.E. at Exeter. Here he was concerned with a dangerous series of experiments on the vulnerability of aircraft to collision with barrage balloon cables, with cable-suspended mines, and with the early work on radio proximity fused bombs.

Subsequently, in 1942, he became Scientific Liaison Officer between the British and Canadian Governments and during this period he inspired the National Research Council in Canada with the idea of building an all-wing aircraft. This resulted in an experimental glider which was flown successfully by Squadron Leader Kronfeld and others, and which provided some useful data for future designs.

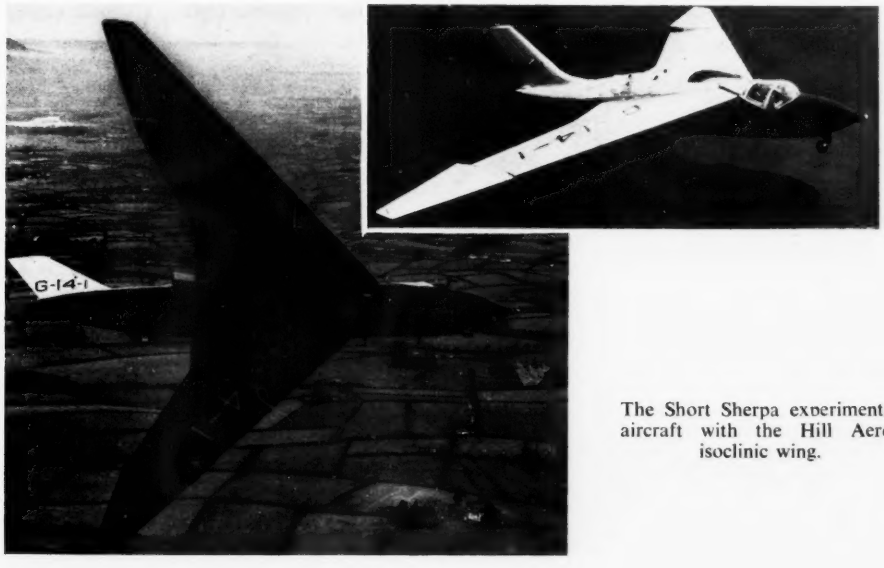
It would be a mistake to think that all Geoffrey Hill's inventive powers were focused on the realisation of a successful tailless aircraft. After the war he was engaged as a consultant to Short Brothers at Rochester and to General Aircraft at Feltham. It is true that he pursued his old line with Shorts, a line which resulted in the "Sherpa," but he also worked on a gust alleviator which he called the " Smooth Ride Flap " and a form of aerodynamic balance for control surfaces which he called " Hill's Holes."



The Pterodactyl Mk. IV three-seater (120 h.p. D.H. Gipsy engine), 1930.

The Smooth Ride Flap was based on the principle that it was unnecessary to eliminate the effects of gusts provided that the effect could be reduced below the threshold value. He defined the threshold value as that at which all normal passengers would retain their breakfasts.

" Hill's Holes " consisted of an ingenious arrangement of three pistons in separate cylinders. The " b_0 " piston was fed with dynamic pressure from the leading edge of the aerofoil, the " b_1 " piston from approximately the points of maximum change of pressure with



The Short Sherpa experimental aircraft with the Hill Aero-isoclinic wing.

incidence and the " b_2 " piston from points near the control hinge. By varying the leaks (holes) across the pistons, " b_0," " b_1 " and " b_2 " could be adjusted, to all intents and purposes, independently.

With General Aircraft, Hill was engaged on the design of a high speed aircraft of variable sweepback. This, in a lesser degree, was a feature of one of his early Pterodactyls where the change of sweep was used as a means of trimming. The General Aircraft design was to have pronounced sweep for high speed and almost no sweep for take-off and landing.

The last of Geoffrey Hill's ideas was the " Aero-isoclinic " wing. As speeds increased and aeroelasticity began to be recognised as a serious problem in aircraft design, he saw a new merit in his old Pterodactyl configuration with the all-moving tip controllers. By substituting these controllers for the conventional elevators and ailerons he saw a way of overcoming the effects on control power and stability which arise from proximity to the control reversal speed. The problem then arose to find a design criterion for the wing stiffness in torsion. Hill, when faced with this problem, took it away for a week and returned with the idea that the torsion box should be placed well aft in the wing so as to get a rearward location of the flexural axis and that the stiffness in torsion and bending should be so adjusted in relation to each other that flexure of the wing would not introduce any of the undesirable loss of incidence at the wing tips which is a feature of normal swept-back wings.

This conception was tried out on the Sherpa, which is a small experimental aircraft built as a scale model of a high altitude bomber. It performs very satisfactorily and has succeeded in demonstrating the soundness of Hill's ideas.

It was a great disappointment to Hill that, in spite of the Sherpa, the conception of the aero-isoclinic wing was never adopted for an operational aircraft. Again he felt that his ideas were not being assessed on their true merits, but were rejected because there was no demonstrable improvement in performance over conventional designs.

He never allowed these disappointments to embitter him but he did allow himself, as a result, to take an impish pleasure in scoring off officialdom. One day, for example, he came into the Mess at Short Brothers beaming all over his face. When asked the reason he said " Today we have got a building licence for one of the buildings we have put up on the farm."

The farm, near Londonderry, was his home and with his wife and two sons he found great pleasure in running it and indulging his skill as an engineer. He designed and fabricated lightweight roof trusses for his buildings and even constructed his own silo in pre-stressed concrete. It was there that he died during Christmas week after being in poor health for about three years.—D. KEITH-LUCAS, *Fellow*.

Free Flight Techniques for High Speed Aerodynamic Research

by

J. A. HAMILTON, M.B.E., B.Sc., A.M.I.Mech.E., A.F.R.Ae.S., aud P. A. HUFTON, M.Sc.
(Royal Aircraft Establishment, Farnborough)

The 969th Lecture to be given before the Society and the 22nd Main Lecture to be held at a Branch Centre, "Free Flight Techniques for High Speed Aerodynamic Research" by J. A. Hamilton, M.B.E., B.Sc., A.M.I.Mech.E., A.F.R.Ae.S., and P. A. Hufton, M.Sc., was given under the auspices of the Boscombe Down Branch on 1st December 1955. Air Commodore R. A. Ramsay Rae, O.B.E., President of the Branch welcomed the guests and said how delighted he was to see the President of the Society, Mr. N. E. Rowe and members of the Council and Main Society at the Aeroplane and Armament Experimental Establishment.

This was the first Main Lecture to be held at Boscombe Down, but they all hoped sincerely that it would be the first of many such occasions at the Branch.

He had great pleasure in welcoming Mr. N. E. Rowe, who was very well known at this Establishment, and handing over the further proceedings of the evening to him.

MR. N. E. ROWE, C.B.E., B.Sc., F.C.G.I., M.I.Mech.E., F.I.A.S., F.R.Ae.S. His duty primarily that evening was to introduce the Lecturers. There had been a little discussion as to the part and proportion that the two Lecturers played and what their relation was to one another. One was the head of the Department and one was, they might say, the worker in the Department, so that expressed the broad relationship. Mr. Hufton they knew well and he would introduce the Lecture and wind it up and Mr. Hamilton would give the body of the paper, which he was sure they would find an extraordinarily interesting one, especially as many of those present were engaged on work of a kindred kind but on rather a different pattern, and he looked forward to a very good discussion.

Mr. Hufton was an M.Sc. of Manchester University; he was at the R.A.E., Aerodynamics Department, was Superintendent of Performance at Boscombe Down for seven years and was now head of the Supersonics Section of the R.A.E. Aerodynamics Department. Mr. Hamilton graduated with a B.Sc. at Edinburgh University in 1943. From 1943 to 1952 he was at the Marine Aircraft Experimental Establishment, latterly in charge of flight research, and since 1952 he had been at the R.A.E. Aerodynamics Department in charge of free flight investigations in the Supersonics Section.

1. Introduction

THE USE of freely flying models to gain an understanding of the laws of flight, dates from the earliest days of aerodynamic experiment. For the aeronautical pioneers simple flying models were one obvious means of putting their theoretical analyses to the test and of acquiring additional physical insight into the mechanics of flight. But the disadvantages of flying models for all but the simplest qualitative tests soon led to their almost complete extinction in favour of the wind tunnel: this eclipse persisted until the problems raised by wind tunnel blockage at near-sonic velocities led to a renaissance of the free-flight technique now enabled, by developments in electronics and rocket propulsion, to provide quantitative information throughout the transonic Mach number range.

With the advent of truly transonic working sections, the tunnel has once more become the primary tool of the aerodynamicist at transonic speeds, but unlike other stop-gap expedients, the free-flight technique has shown virtues which have gained it a place with full-scale flight and the tunnel, as a research facility in its own right, at high supersonic as well as at transonic speeds.

2. Early Developments

Three main forms of free-flight* experiment have been tried in the United Kingdom. They are:

(*a*) Those employing powered, air-launched test vehicles.

(*b*) Those employing unpowered, air-launched test vehicles.

(*c*) Those employing powered, ground-launched test vehicles.

The initial effort on free-flight development went into a powered air-launched test vehicle—the R.A.E. Vickers rocket model.[1] This was a model aircraft with unswept wings, having a length of 11 ft. and a wing span of 8 ft. (Fig. 3). Propulsion was by liquid-fuel rocket motor using a mixture of methyl alcohol and hydrazine hydrate as a fuel and concentrated hydrogen peroxide

*In this context and elsewhere throughout the paper the term "free-flight" appertains to aerodynamic experiments at transonic and supersonic speeds. Investigations into low-speed aerodynamic problems have also been made using freely flying models, *e.g.* take-off and landing, and spinning. These are not considered here.

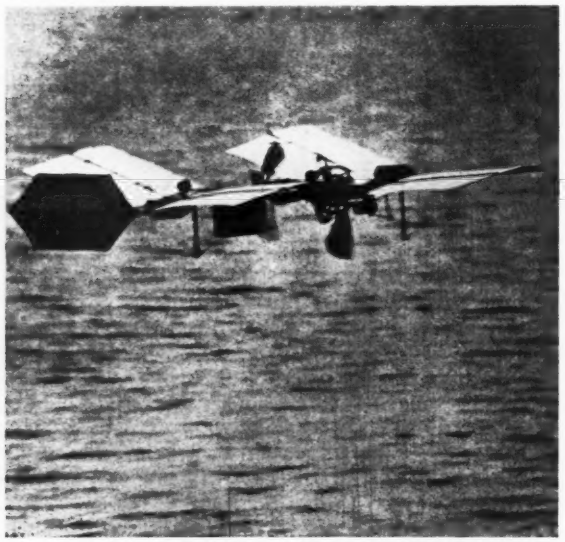


FIGURE 1. 1903: Langley quarter-size model. $M = 0{\cdot}04$.

as an oxidant. The aim was to release the model from its parent aircraft (a Mosquito) at a height of 36,000 ft. and a speed of 400 m.p.h.: once released it was propelled by the rocket motor to supersonic velocity and controlled in straight and level flight by means of an autopilot. During its flight the model was tracked from a ground station by radar and its behaviour recorded by radio telemetry.

The fate of this investigation is now well-known. Mechanical and electronic problems raised by the complicated and advanced nature of the model and its rocket motor, engulfed the project from its inception: to these problems were added the operational difficulties of a complex ground and air organisation when flight-test work began. After a long and troubled period of gestation a successful *modus operandi* was evolved, but by that time, more economical methods of investigating transonic flight had been developed and the project was abandoned before it had produced any results of value.

More success was achieved with unpowered airborne test vehicles[2] (Fig. 4). These were also equipped with telemetry and tracked by radar but obtained the required transonic velocities in free fall. This technique is still in use in the United States and to a lesser extent in this country for bomb-ballistic work; its major drawback, apart from the operational difficulties, is the limited Mach number range which can be covered by one model. For aircraft-model work it has been abandoned in the United Kingdom in favour of the powered ground-launched model.

FIGURE 3. R.A.E.-Vickers air-launched rocket model. Weight 900 lb.

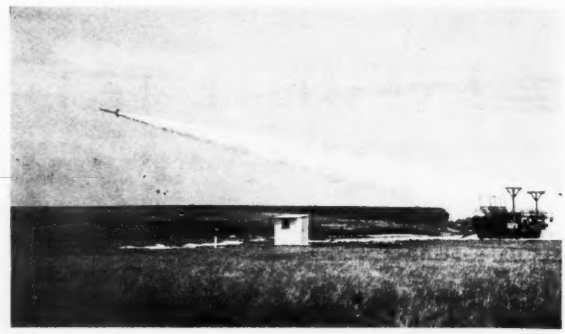


FIGURE 2. 1953: R.A.E. rocket model. $M = 2{\cdot}5$.

Many factors influenced this choice of technique but the over-riding one was the operational simplicity of launching from the ground compared with air launching. The relative compactness of the range layout for ground-launched trials eases the problem of controlling the experiment and introduces that high degree of flexibility which is necessary when dealing with test vehicles of unconventional design—and often unconventional behaviour! In ground-launched free-flight tests the aircraft or component model is launched from a simple platform and accelerated to the maximum required velocity by a solid-fuel rocket motor. After the motor has ceased to burn—the propulsion period usually occupies no more than two or three seconds—the model decelerates in coasting flight to cover the necessary Mach number range. During the period of coasting flight the behaviour of the model is recorded externally by electronic and optical means and internally by radio telemetry.

The remainder of this paper is concerned only with the ground-launched model method of free-flight aerodynamic research.

3. Recording Methods

An average time of flight for a rocket-propelled aerodynamic test vehicle is 12 seconds. Within this period the vehicle is accelerated from rest to a maximum Mach number of say 1·5 and then decelerated to subsonic velocity: the total distance covered is 3 or 4 miles

FIGURE 4. R.A.E. air-launched unpowered model.

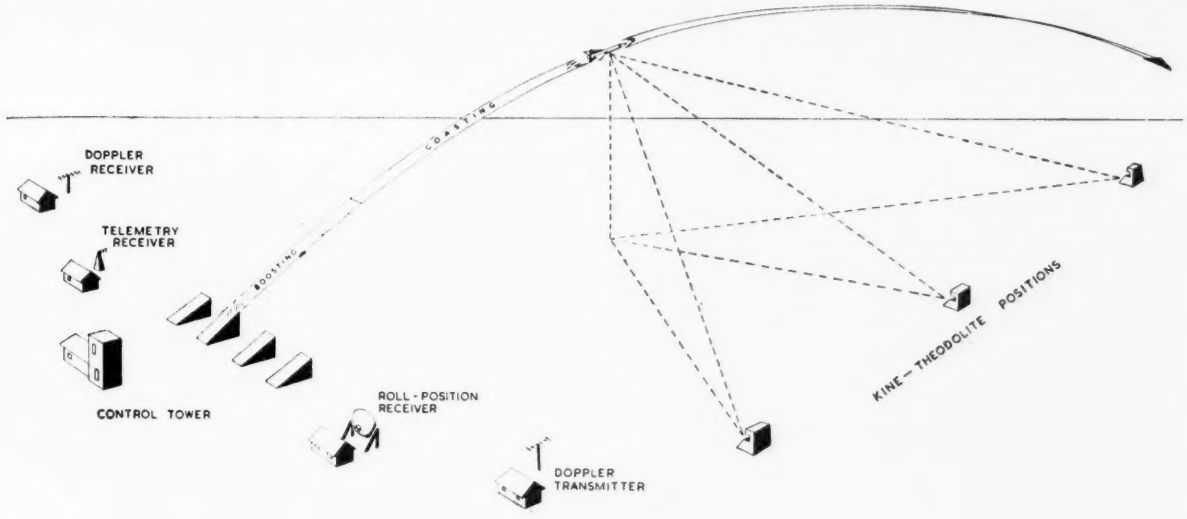


FIGURE 5. Range layout.

and the maximum height achieved about 2,000 ft. During its flight the model may be rolling continuously at rates of roll up to 3,000 deg/sec. or oscillating continuously in pitch with frequencies of the order of 12 cycles/sec. The problem of recording the behaviour of such a short-lived body is manifestly a formidable one and its solution has given rise to a new and esoteric branch of instrument and electronic engineering.

Associated with these developments is the establishment and operation of the complex ground organisation at the trials range. The responsibility for this service, whether for aircraft model or missile trials, rests with the Guided Weapons Trials Department of the Royal Aircraft Establishment. Indeed most of the recording methods described here owe their inception to the need for guided-missile flight trials, and the aerodynamic free-flight technique is fortunate in having at its disposal not only the instrument and electronic developments prompted by the guided missile, but also the associated production facilities. It is doubtful whether the free-flight technique would have been successful in its present form without this help from the missile groups.

3.1. EXTERNAL MEASUREMENTS

The three principal external measurements are those of *trajectory*, *velocity* and *position in roll*. *Trajectory* is obtained optically by having several kine-theodolites spaced at suitable intervals along the proposed direction of flight (Fig. 5). These give simultaneous records of the bearing and elevation of the test vehicle at intervals of 1/5th of a second throughout its flight (Fig. 6). Simultaneity is ensured by having the shutter of each camera operated from a central timing source which also supplies timing to all other range facilities and thus eliminates errors owing to incorrect synchronisation between the various forms of record involved.

Velocity is measured by a radio-Doppler system which beats a constant-frequency radio signal against its echo from the moving test vehicle. Thus, the apparatus measures the change in the distance, transmitter—vehicle—receiver, and compares this with a time base: knowing the trajectory of the model this information can be converted into line-of-flight velocity. If the theodolite and Doppler records are of reasonable quality, the line-of-flight velocity can be determined to within ± 2 ft./sec.

Using a numerical double-differentiation process the Doppler record can be made to yield longitudinal acceleration and hence drag. The accuracy obtained in drag measurement using Doppler is dependent upon the rate of change of drag with time: where this is high, *e.g.* at near-sonic Mach numbers, the Doppler calculation tends to round off sudden variations in drag.

Many free-flight tests require a measurement of rate of roll, and although this can be obtained by a telemetered measurement taken within the model, the more usual method is to use a specially designed roll-position indicator (Fig. 7). The operation of this apparatus depends upon the ability of certain shapes of aerial to

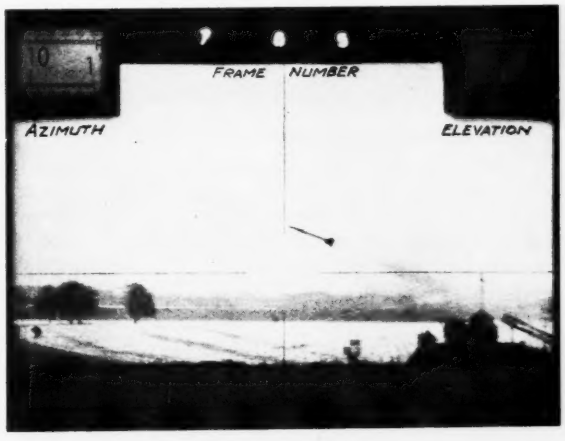


FIGURE 6. Kine-theodolite record. (Frame speed 5 per second).

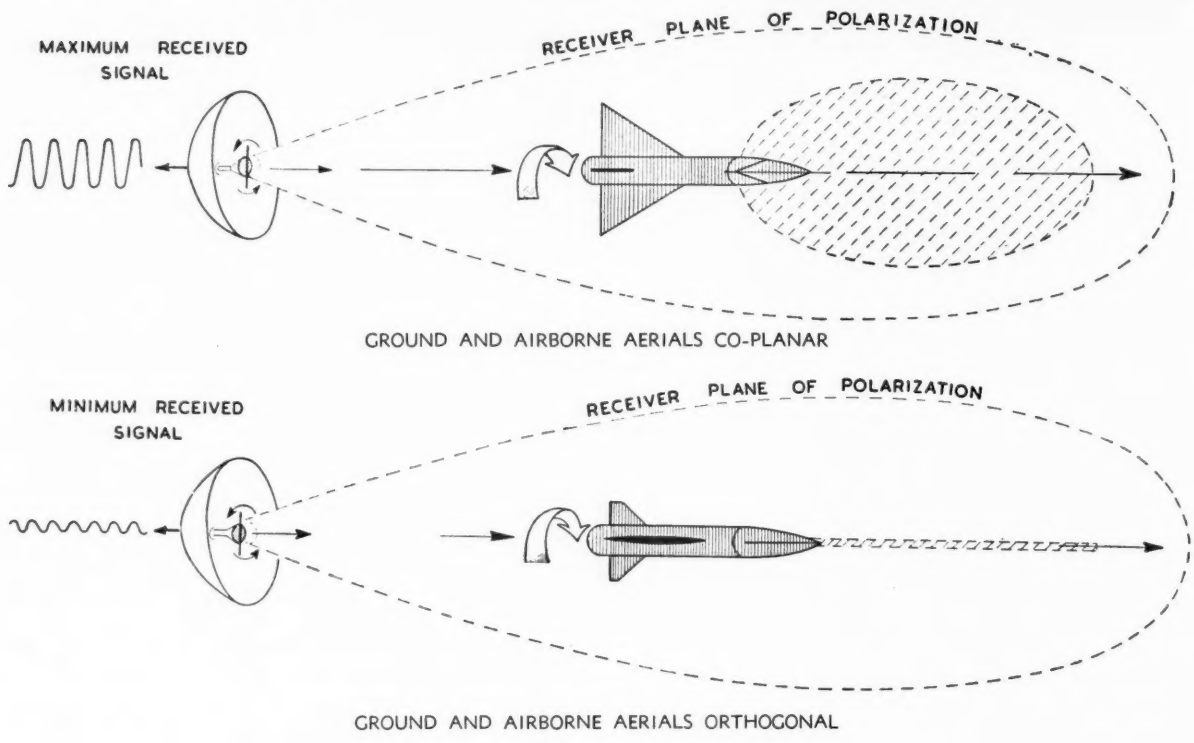

MAXIMUM RECEIVED SIGNAL
RECEIVER PLANE OF POLARIZATION
GROUND AND AIRBORNE AERIALS CO-PLANAR
MINIMUM RECEIVED SIGNAL
RECEIVER PLANE OF POLARIZATION
GROUND AND AIRBORNE AERIALS ORTHOGONAL

FIGURE 7. Roll position measurement.

give plane-polarised signals. The rolling test vehicle contains a transmitter (spinsonde) with a constant-frequency oscillator radiating through a half-wave dipole; the signals from this are received by a ground unit having a polarisation-sensitive aerial system. When the planes of the transmitting and receiving aerials are orthogonal then the received signal is a minimum: when they are co-planar the received signal is a maximum. Thus, by noting the maxima and minima, the roll position of the vehicle at intervals of 90 degrees may be deduced: in practice the ground aerial is also made to rotate at 45 rev./sec. (in the opposite direction to that of the model) and the maxima and minima then occur at about 180 times per revolution, thus giving improved definition of position.

3.2. INTERNAL MEASUREMENTS

3.2.1. *Airborne Component*

Measurements of force, moment, pressure, incidence, etc. are taken within the test vehicle itself and transmitted to a ground-recording station by an airborne telemetry unit (Fig. 8). The unit normally used for aerodynamic investigations works on a time-multiplex system* with a carrier frequency of 465 Mcs., modulated in the range 130-160 kcs. by the variables being measured. There are four main components in each unit: the physical quantities to be measured are converted into electrical quantities by variable-inductance transducers of the kind illustrated in Fig. 9; each transducer is connected to one or more contacts on a 24-point, electrically-driven scanning switch. The transducers in conjunction with the so-called 'modulator' form a tuned circuit in which the variations in inductance are converted into frequencies in the 130-160 kcs. band. These frequency variations are then used to amplitude-modulate the 465 Mcs. carrier wave generated by the R.F. oscillator which is the final link to the transmitting aerial.

The switch employs a motor-driven contact arm rotating at approximately 120 rev./sec. This gives adequate definition for most purposes but where a transient or cyclic variable is being recorded the appropriate transducer can be connected to two or more contacts, thus giving improved definition in return for a reduction in the number of variables which can be recorded.

In most transducers the armature is cantilever-mounted on two leaf-springs, the full-scale deflection being such as to give a movement of the armature relative to the coil of 0·01 in. This gives a robust instrument with an accuracy of $\pm$ 2 per cent. of full-scale deflection and an adequately high natural frequency for the conventional free-flight techniques*.

i.e. the information from the various transducers is not transmitted simultaneously on different channels but in a fixed time sequence on a single transmission wave.

*For example in dynamic longitudinal stability studies the model pitching frequency is between 10 and 15 c.p.s. and the natural frequency of the linear accelerometer transducers used to record lift force and moment is about 120 c.p.s., associated with a damping coefficient near the optimum 65 per cent. of critical.

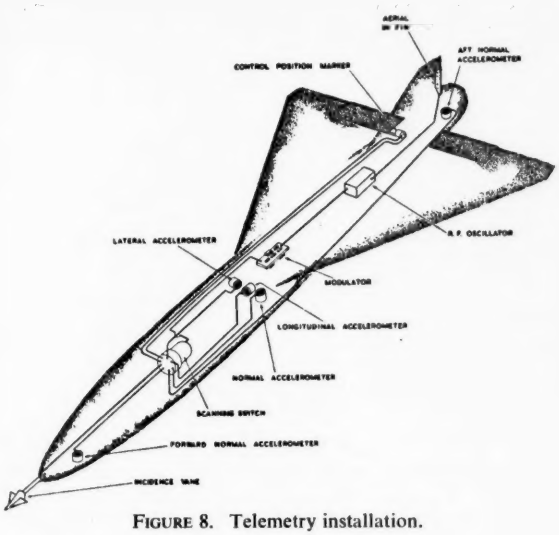


FIGURE 8. Telemetry installation.

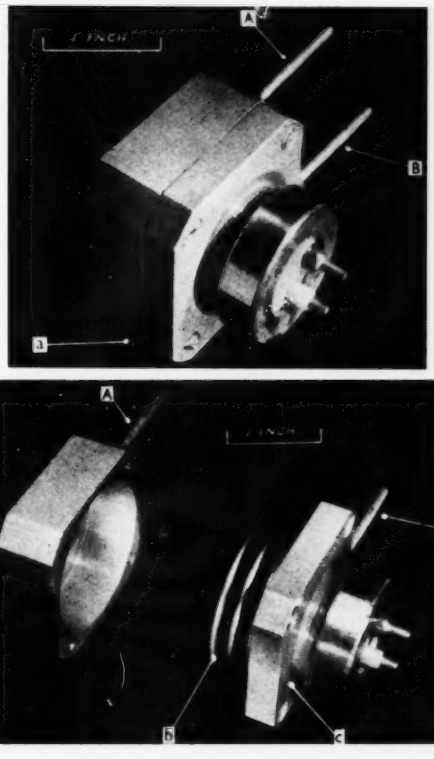
Such transducers are available for measuring linear acceleration, angular acceleration, pressure and incidence. The incidence vane is a good example of the design ingenuity which has to be exercised to meet the requirements of free-flight work*. An incidence vane must be robust enough to cope with longitudinal accelerations of 50*g* and transverse accelerations of 30*g*: bearing friction must be low because of the high longitudinal loading at high Mach numbers and a close static balance must be achieved, otherwise the transverse accelerations occurring during dynamic stability manoeuvres will introduce out-of-balance errors: all this to be attained with a total incidence range of $\pm 5°$ and an accuracy of $\pm 0{\cdot}1°$. The instrument as finally designed is illustrated in Fig. 10: by making the armature integral with the rotating vane and the coil integral with the sting which is attached to the model, strength and accuracy have been achieved in the minimum space.

An important factor in the efficiency of the airborne telemetry radiation is the aerial system, and in many free-flight tests a good aerial installation must be obtained without interfering with the external shape of the model. For models with wooden fins this can be achieved by embedding a copper strip in the fin: for metallic fins a slot aerial replaces the simple strip.

3.2.2. *Telemetry Ground Unit*

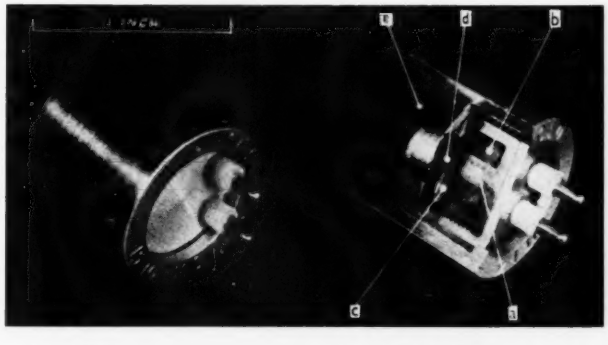
The principal function of the ground receiving equipment is to convert the frequencies in the 130-160 kcs. band into equivalent displacements, and record these for the purpose of analysis. There are two principal means of presentation; in the first the outputs from each contact on the airborne scanning switch are displayed sequentially in time as deflections on a single cathode-ray oscilloscope and recorded on 35 mm. film (Histogram, Fig. 11). This is the more accurate record

*This and the other transducers described here were designed and developed by the Instrumentation Department of the Royal Aircraft Establishment.



(*a*) Complete transducer.
(*b*) Spring-loaded bellows.
(*A*) Pressure inlet (high pressure chamber).
(*B*) Reference pressure (low pressure chamber).
(*c*) Housing.

PRESSURE TRANSDUCER



(*a*) Core.
(*b*) Coil.
(*c*) Armature.
(*d*) Leaf spring.
(*e*) Expansion chamber.
Weight: 1 oz.

LINEAR ACCELERATION TRANSDUCER

FIGURE 9. Typical variable inductance transducers.

but because of the method of presentation it does not lend itself to a quick qualitative appreciation of the results from a flight test: such a quick appreciation may be important when a series of models is being fired and the results from those already flown may affect the flight programme of those remaining. An alternative record allows this qualitative assessment by having a series of oscilloscopes; these oscilloscopes record only

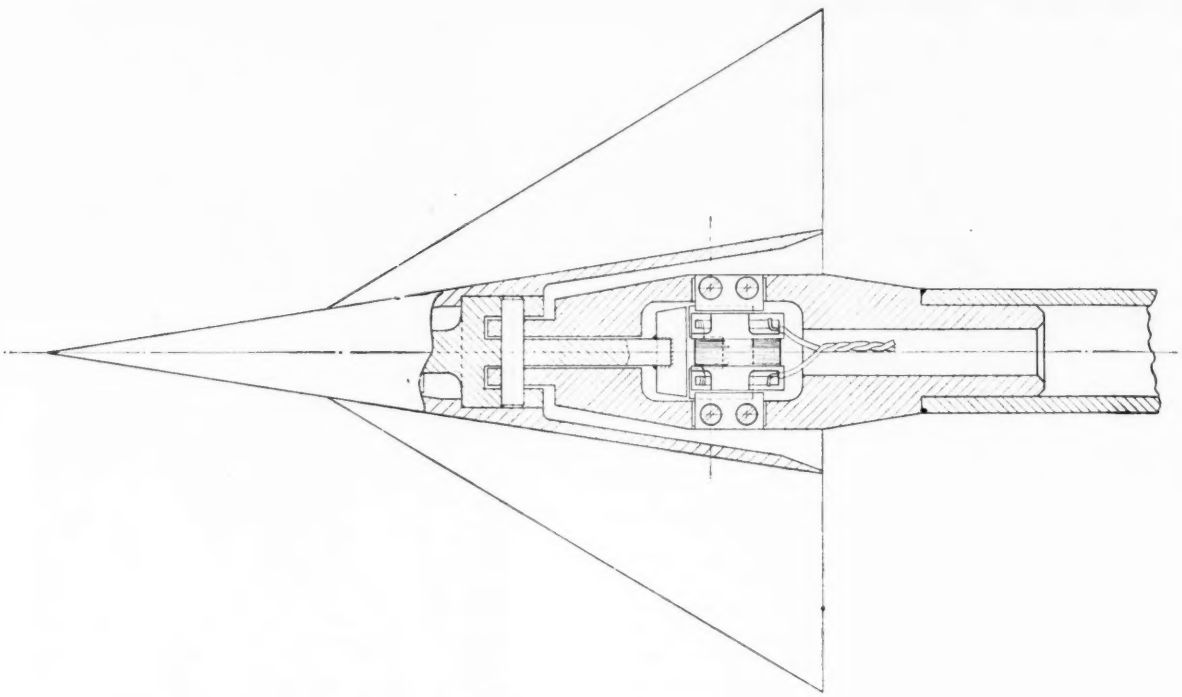


FIGURE 10. Incidence vane.

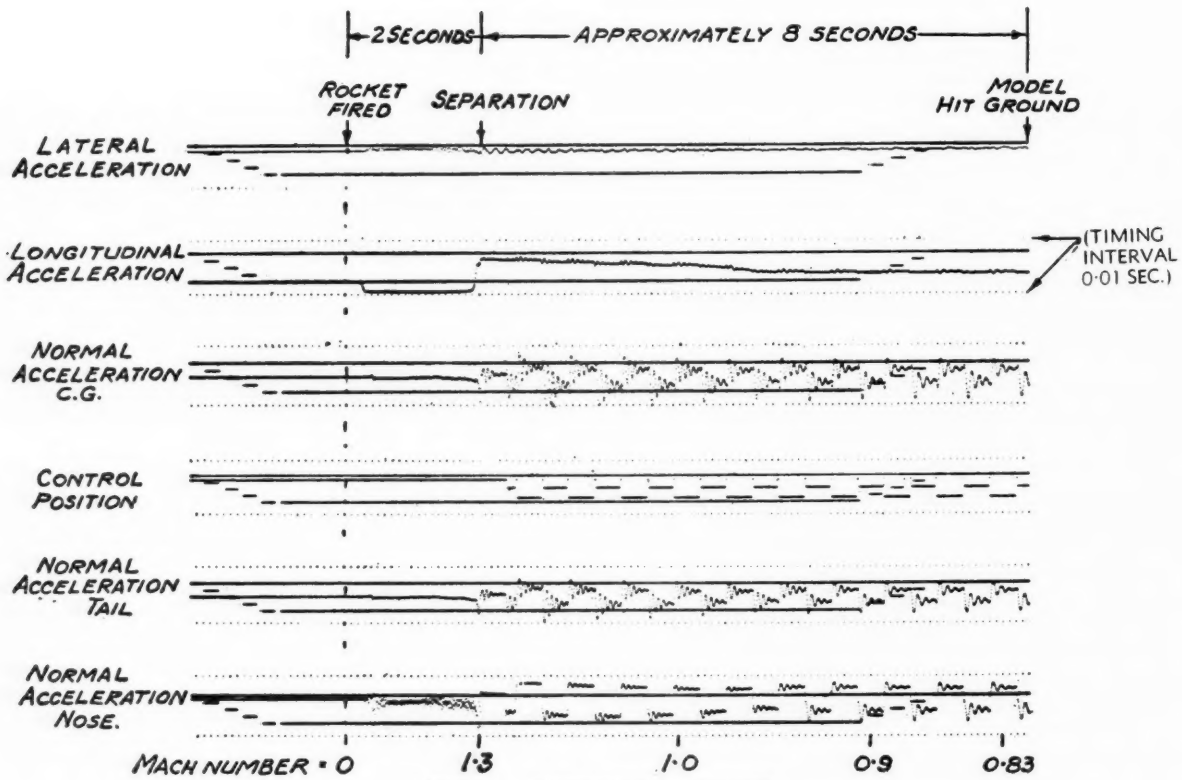


FIGURE 12. Telemetry record—panorama.

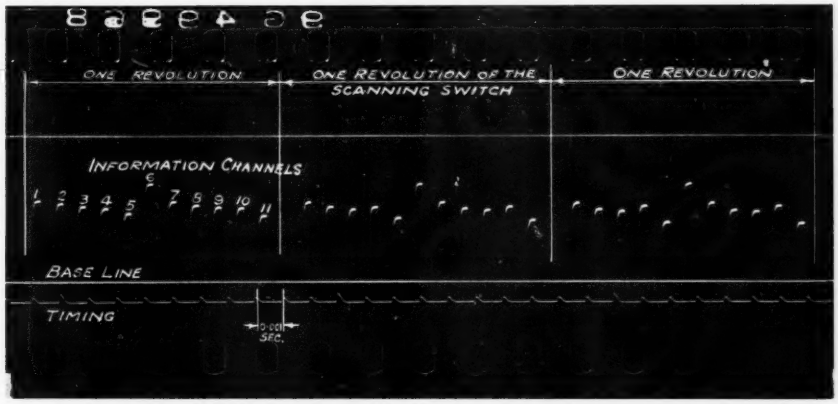


FIGURE 11. Telemetry record—histogram.

when the scanning arm of the switch is on the appropriate contact and by arranging them side-by-side the individual transducer readings can be made to appear as separate record lines on a single negative. (Fig. 12).

3.2.3. *Calibration*

Since, for nearly all test vehicles, post-flight calibration is impossible, the need for accurate and rapid pre-flight calibration is paramount. A fundamental requirement for reliable results is that transducers should be calibrated with the telemetry unit to be used in the flight test and this, combined with the other desiderata, has led to the development of calibration apparatus specifically for free-flight instrument installations. A good example of such a device is the incidence vane calibrator illustrated in Fig. 13. The usual procedure is to install the vane in the model, align it with a known longitudinal axis and then calibrate *in situ*. The calibrator is clamped to the support sting and rotates the vane by a worm and wheel motion: the frame and quadrant are spring-loaded to ensure freedom from backlash.

Linear accelerometers are calibrated in the usual fashion on a turntable (Fig. 14). The example shown has two special features: the drive is by means of a compressed-air jet impinging on a series of peripheral vanes to avoid extraneous vibration and the speed measurement is obtained by counting the output of a photo-electric cell activated by about a thousand small holes drilled around the turntable circumference. Angular accelerometers are calibrated on an oscillating table and pressure transducers by comparison with a manometer.

3.3. METEOROLOGICAL OBSERVATIONS

Observations of ground barometric pressure and ambient temperature are taken throughout the trials by a meteorological station at the range head. The meteorological staff also measure wind velocities over the operating range of altitude by the balloon-tracking method.

Temperature and pressure at altitude are not recorded locally but are interpolated from radio-sonde measurements taken at major meteorological stations in the south of England.

4. Models and Techniques

In free-flight testing the complexity of a model is greatly dependent upon whether or not it has to obtain information under lifting conditions. Obviously if a stable axisymmetric test vehicle is undisturbed during its flight it will fly at zero lift: such test vehicles are of relatively simple construction, for the rocket motor can usually be made an integral part of the structure and no disturbance mechanism is necessary (Fig. 15). These are termed non-separating models. For those investigations where the model has to pitch (or yaw) some form of control or rocket disturbance is necessary and this, combined with the need for more design freedom in determining model c.g. positions and inertias, precludes the use of integral construction. Such models are therefore designed and manufactured as separate units and attached to one or more rocket booster motors by a simple spigot or hook which allows the two to separate

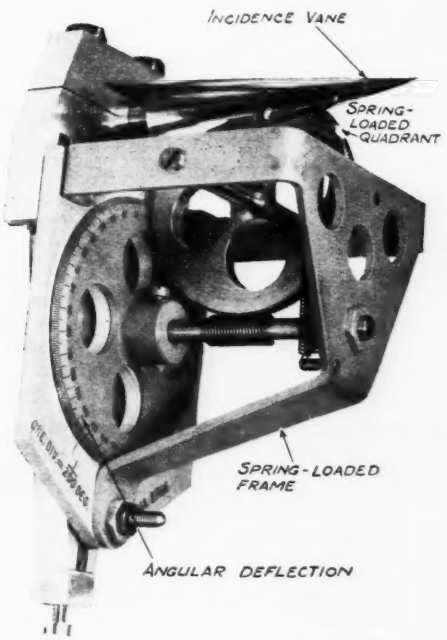


FIGURE 13. Incidence vane calibrator.

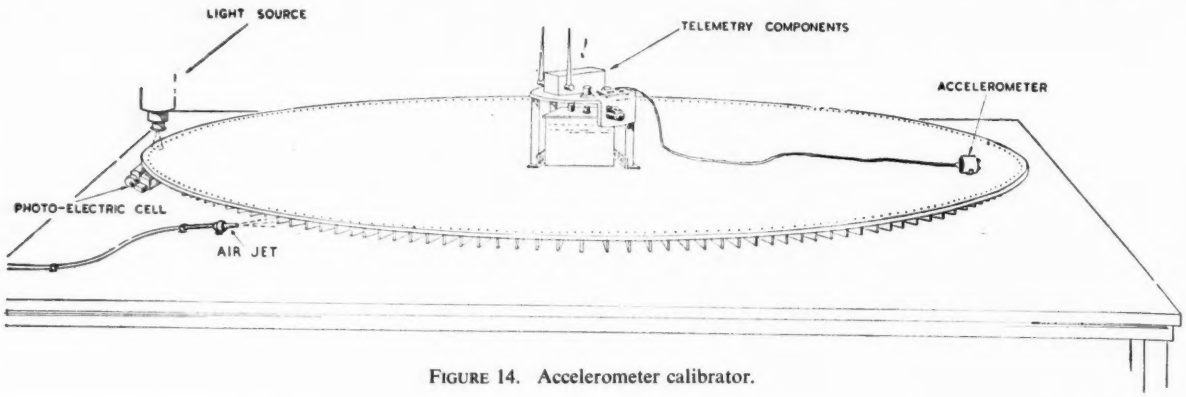


FIGURE 14. Accelerometer calibrator.

automatically when the rocket motor has ceased to burn. The model then flies on by itself, performing its predetermined programme of manoeuvres. This separating-model technique is also applied to zero-lift investigations on specific aircraft designs which are rarely of such shape as to allow incorporation of a rocket motor. (Fig. 16).

Although the separating test vehicle is the more flexible instrument, it presents two major headaches to the designer from which the simpler integral rounds are mercifully free. These are the associated problems of ensuring that the rocket and model combination does not develop lift during the boosting period and that the model separates from the rocket in an orderly manner. The first difficulty arises mainly from downwash on the rocket fins induced by the model wings: it can be minimised by careful choice of the model position on the rocket and by having a high static margin for the combination. Good separation is achieved by ensuring that the drag/weight ratio for the model is low compared with the rocket motor and, for pick-a-back vehicles, by designing the attachment hook to lift the model clear as it moves forward. These difficulties are, in general, less severe for tandem arrangements than they are for pick-a-back, but to avoid loss of accurately manufactured models, it is normal practice to fire a roughly made model to confirm that boosting and separation are satisfactory.

4.1. TESTS ON CONTROLS

4.1.1. *Measurement of Rolling Effectiveness*

One of the earliest successful applications of the free-flight technique was to the investigation of aileron rolling power at transonic speeds. This problem—it might almost be described as a classic now—brought to light one of the first manifestations of shock-induced boundary layer separations and it provides an interesting commentary on the relationship between tunnel and free-flight work.

The simplest kind of control test vehicle employs wings with fixed-deflection controls as shown in Fig. 17. The model is of integral construction: to the 5 in.-diameter rocket motor is attached a resin-bonded-paper tube which provides a smooth outer surface and a means of attaching the test wings. These tubes are ideal for this purpose; besides giving a smooth surface they are light and rigid, and easily machined. The spinsonde telemetry transmitter is contained in a Perspex ogival nose (Fig. 18) and the three wings with their controls deflected (usually at 5 degrees) are glued into a thickened portion of the tubular casing at the tail of the vehicle. Each of the wings is manufactured individually,

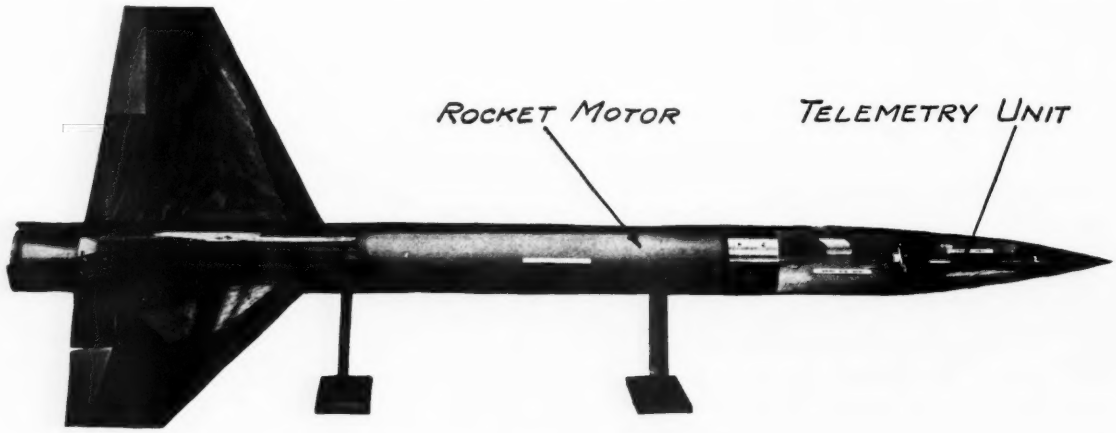


FIGURE 15. A non-separating test vehicle.

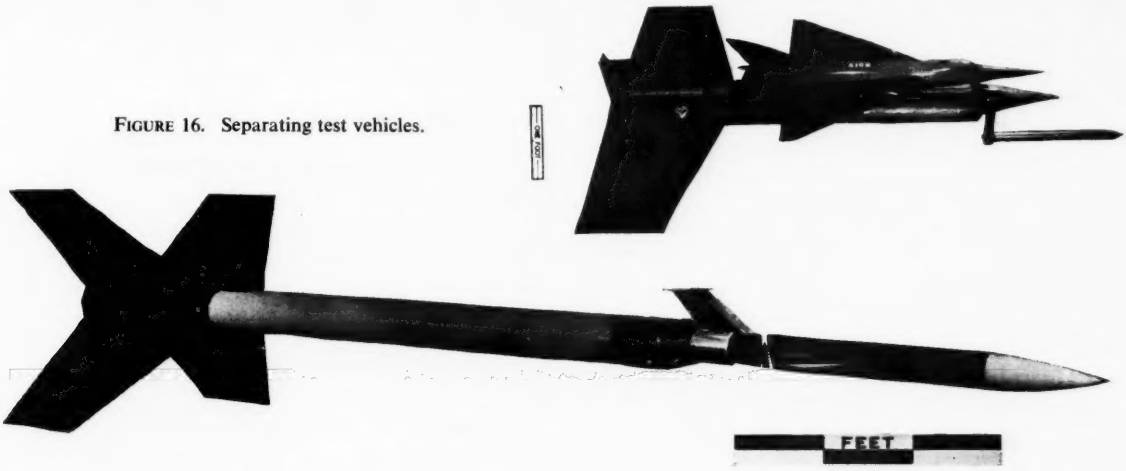


FIGURE 16. Separating test vehicles.

usually in compressed wood, and the deflected controls pinned and glued into position. For thin wings a light alloy laminated core is incorporated to provide torsional stiffness and the control may also be manufactured from light alloy to avoid spurious results owing to control distortion. To counteract the effect of any inherent spanwise twist in the wing, each wing is glued into the body with a root setting angle calculated to give zero net lift over the wing panel in the absence of the control.

Because of its deflected controls the test vehicle rolls continuously during its flight. Rate of roll and acceleration in roll may be derived from the spinsonde system described earlier, and velocity is obtained by Doppler measurement. The primary parameters involved are, of course, rate of roll and Mach number: a knowledge of roll acceleration is necessary to correct the transient roll conditions of the test flight to steady roll conditions. (*See* Appendix I). The final result is, therefore, a curve of wing-tip helix angle $(pb/2V\xi) = -l_\xi/l_p$) against Mach number. (Fig. 19).

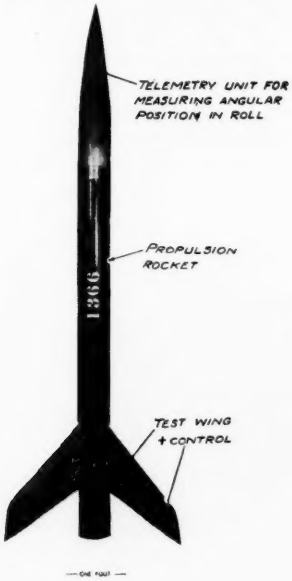


FIGURE 17. Test vehicle for the measurement of aileron effectiveness.

The relative simplicity of this technique makes it suitable for obtaining quick results on the influence of variations in control and wing geometry on control effectiveness. An example of this is the confirmation obtained in free flight of the general results of shock wave, boundary layer interaction deduced by Holder *et al* from wind tunnel tests at the National Physical Laboratory.[3] The increasing 'dip' in transonic control effectiveness with increasing wing thickness: chord ratio can be directly related to the two-dimensional N.P.L. tests and thence to the physical picture deduced from these tests.

4.1.2. *Measurement of Damping in Roll*

Although of obvious interest *per se* the evaluation of the damping-in-roll derivative l_p is also an essential adjunct to the simple fixed-control technique if the control effectiveness derivative l_ξ is to be isolated. To measure l_p in free flight the test wings are mounted on a sting ahead of the main body of the test vehicle. (Fig. 20). The whole test vehicle is made to roll continuously during its flight by offset fins attached to the rear end, and the problem of measuring roll damping is then reduced to that of measuring the torque in the sting connecting the test wings to the rocket motor. Initially several schemes involving the use of helical springs were tried for torque measurement but these proved to be unreliable in flight and complicated to manufacture. They were, therefore, abandoned in favour of the simple and robust arrangement now in use.* In this, the angular displacement of the sting is

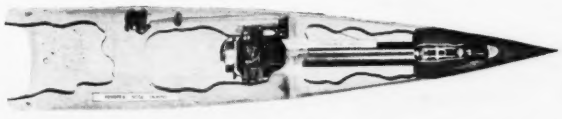


FIGURE 18. Telemetry installation for the measurement of roll position (Spinsonde).

*The design and development of this unit is due to K. J. Turner, of Aerodynamics Department, R.A.E.

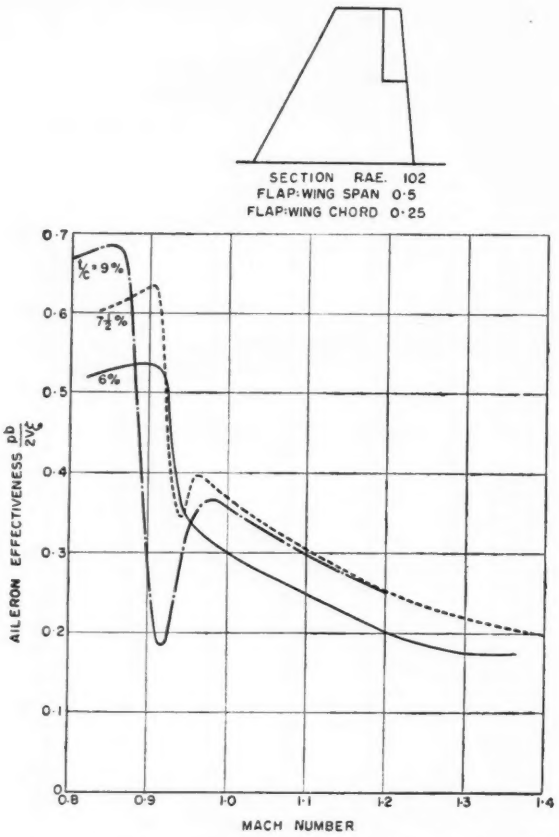


FIGURE 19. Measurement of aileron effectiveness using fixed deflection controls.

magnified by means of a small lever arm and the movement of the lever arm is measured by an armature and coil arrangement similar to that used in the standard variable-inductance telemetry transducers (Fig. 21). To eliminate errors arising from bending, the sting is supported by three ball races, two of which straddle the torque-measuring element. The whole system is calibrated by applying known torques to the sting immediately before flight. Since the damping is being measured continuously throughout the flight, this technique is able to detect the very rapid changes in the derivative which may occur at near-sonic speeds. (Fig. 22).

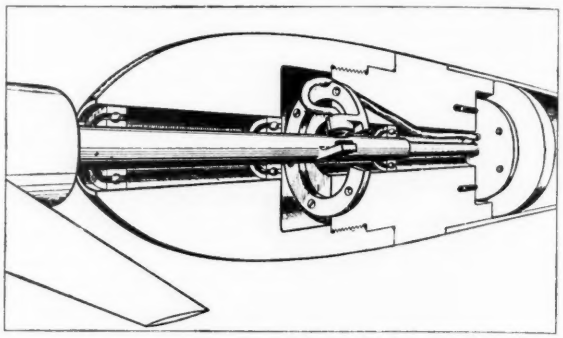


FIGURE 21. Mechanism for measuring damping in roll.

4.1.3. *Measurement of Hinge Moment*

By employing a rolling model with actuated controls, simultaneous measurements of l_p, l_ξ and hinge moment may be obtained. Such models are invariably of the separating kind, *i.e.* when the booster motor has ceased to burn it falls away and the model flies on by itself. When separation occurs, a timing device within the model starts the pneumatic control system which then operates the controls in a square-wave pattern with a period of about 0·5 sec. (Fig. 23). As a result, the model performs a series of alternating rolls to port and starboard: from simultaneous measurements of rate of roll (spinsonde) and acceleration in roll (telemetered angular accelerometer) the roll response may be analysed to give l_p and l_ξ (Appendix I) (Fig. 24). Hinge moment is obtained by measuring the torque in the flap-operating rod using a mechanism similar to that of the l_p-measuring device described in the previous section.

The major advantage of this technique is its ability to give information on hinge moment. The considerable complication of the actuated control system and its liability to miss rapid changes in the derivatives make it less suitable for the determination of l_p and l_ξ than the two simpler techniques described in 4.1.1. and 4.1.2.

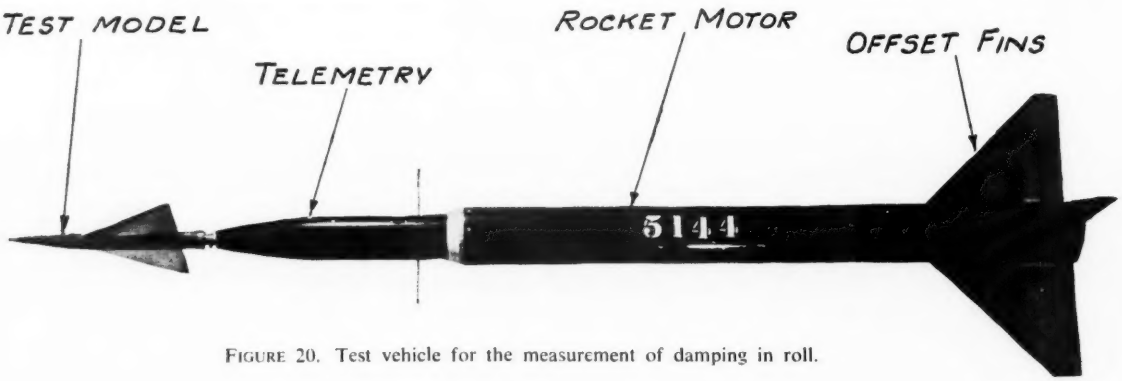


FIGURE 20. Test vehicle for the measurement of damping in roll.

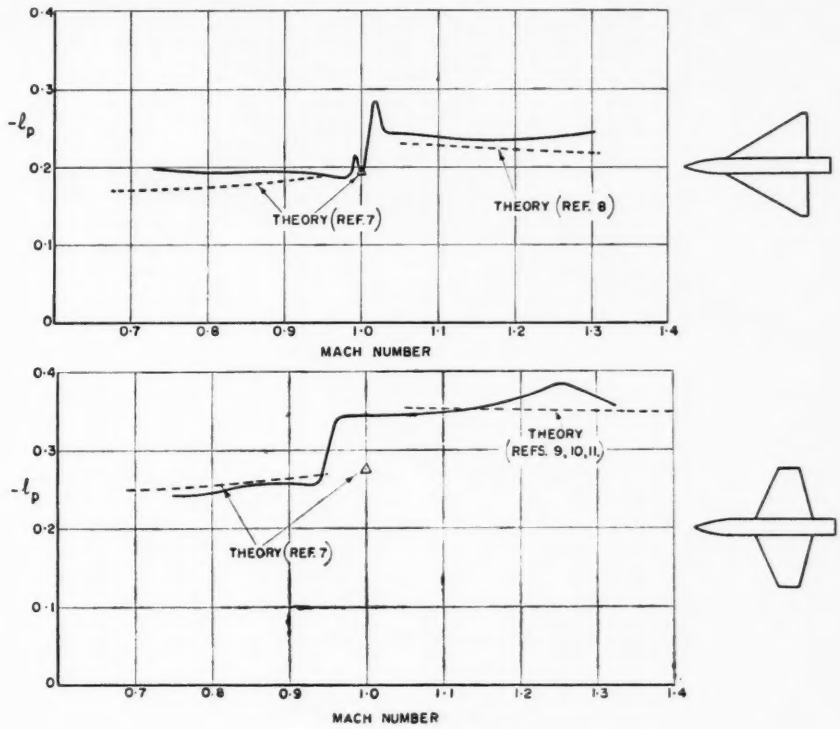


FIGURE 22. Roll damping results.

4.2. MEASUREMENT OF DRAG AT ZERO LIFT

In free-flight work a distinction must be made between the measurement of drag at zero lift and the measurement of drag due to lift. The latter is usually obtained as a by-product of the longitudinal stability technique described in Section 4.3. and involves a much more complex model and instrument installation than does the zero-lift measurement. Indeed, the simplicity of zero-lift drag determination in free flight is one of the major arguments for the existence of the technique as a complement to the transonic tunnel.

Initially the primary concern of transonic and supersonic drag investigations was the measurement of wing drag. The limitations of the linearised theory of supersonic flow in predicting wing wave drag are well known, and the aim was to provide a framework of experimental results filling in the regions of doubtful theoretical applicability. To accomplish this a number of vehicles of the kind illustrated in Fig. 25 were flown. In these, the test wings are clamped to the rocket motor and a smooth exterior surface provided by a resin-bonded paper tube covering wing fixings and rocket: a low-drag ogival nose contains the single-channel telemetry unit measuring longitudinal acceleration. Since the measurements are confined to the coasting period, all that is needed for drag coefficient evaluation is a knowledge of speed, height, model weight and acceleration. Speed is obtained from Doppler, and acceleration from Doppler and telemetered accelerometer records. Both are used because while the Doppler measurement is more accurate where the drag variation with Mach

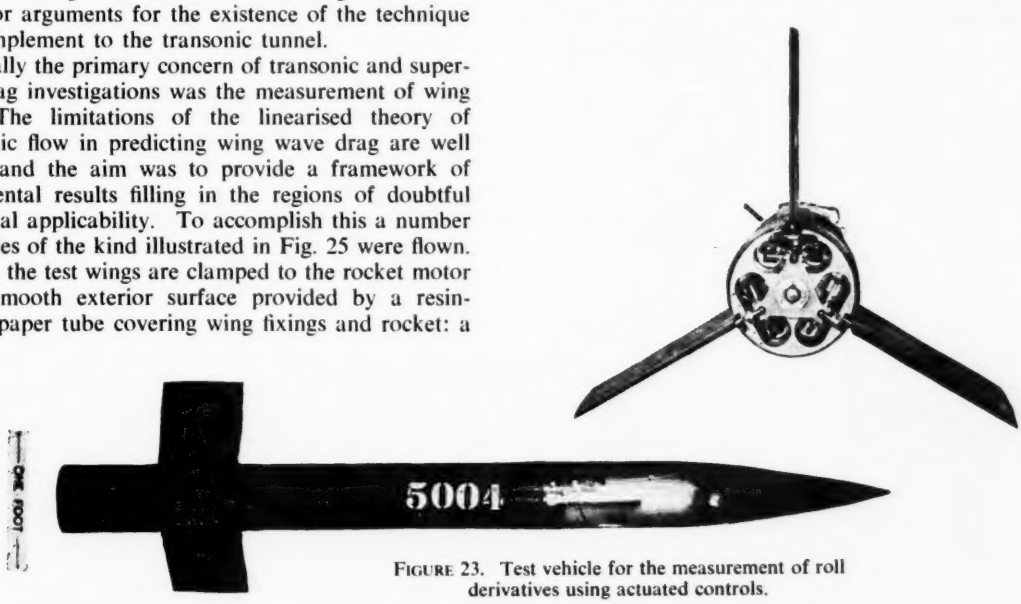


FIGURE 23. Test vehicle for the measurement of roll derivatives using actuated controls.

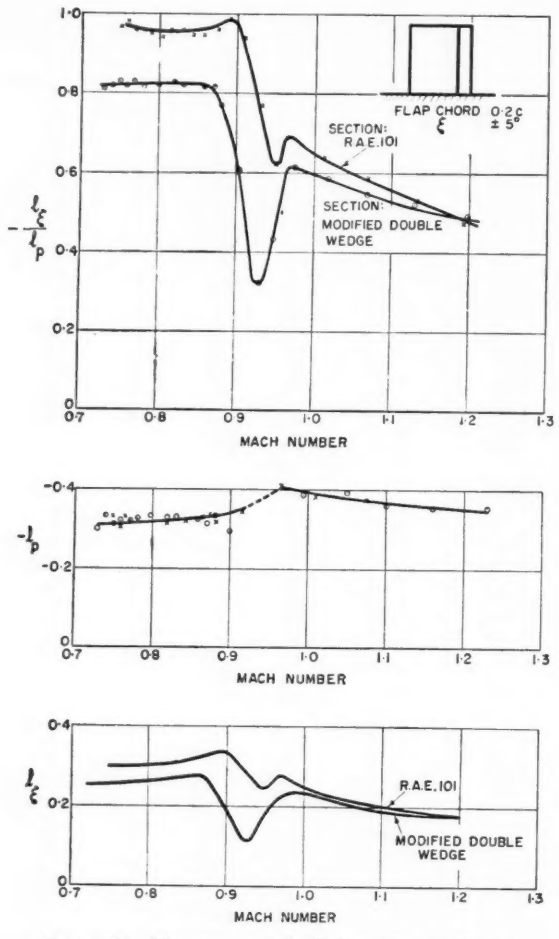


FIGURE 24. Measurement of roll damping and aileron effectiveness using actuated controls.

FIGURE 25. Test vehicle for the determination of wing drag at zero lift.

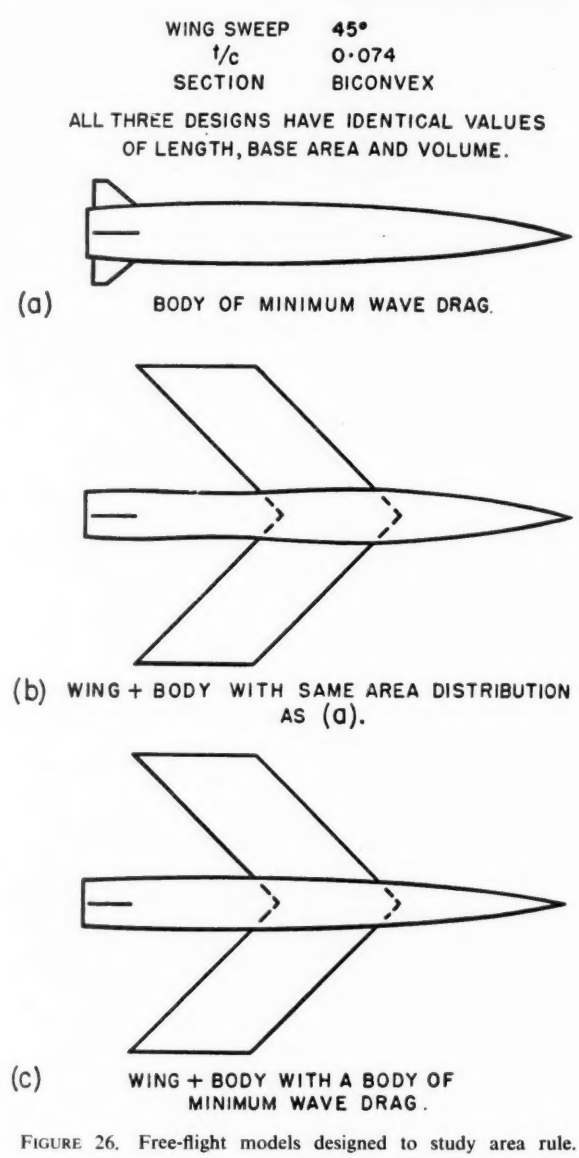

WING SWEEP 45°
t/c 0·074
SECTION BICONVEX
ALL THREE DESIGNS HAVE IDENTICAL VALUES OF LENGTH, BASE AREA AND VOLUME.
(a) BODY OF MINIMUM WAVE DRAG.
(b) WING + BODY WITH SAME AREA DISTRIBUTION AS (a).
(c) WING + BODY WITH A BODY OF MINIMUM WAVE DRAG.

FIGURE 26. Free-flight models designed to study area rule.

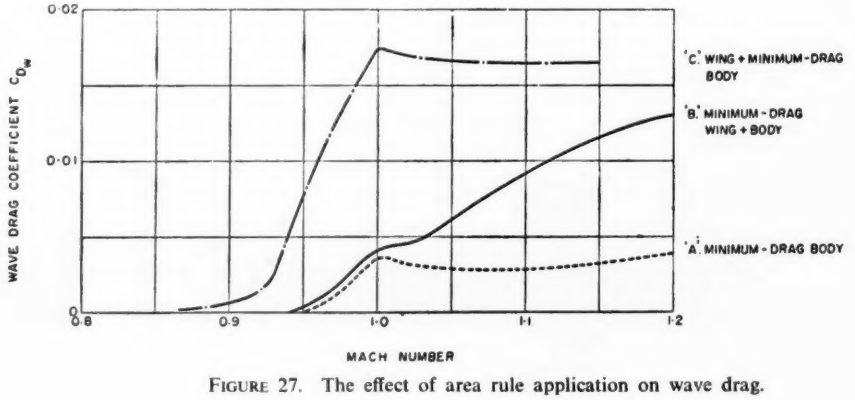


FIGURE 27. The effect of area rule application on wave drag.

FIGURE 28. A typical model for the measurement of intake efficiency and overall drag at zero lift.

number is relatively small, *i.e.* at subsonic and supersonic speeds, at transonic speeds where rapid changes occur, the direct accelerometer measurement gives the more faithful record.

Having thus determined the drag of the whole test vehicle, the drag of the wing alone was deduced from this, and the known drag of the isolated central body. This process of drag subtraction takes no account of possible interference between wing and body, and although the model design is such as to keep interference drag to a minimum, the wing drag eventually derived is, in fact, wing + interference drag.

Considerable doubt was cast on the usefulness of these " isolated-wing " drag tests by the advent of the transonic area rule method for designing low-drag wing-body combinations*. In its simplest form the area rule states that all bodies, wings and wing-body combinations having the same axial distribution of cross-sectional areas, will have the same wave drag at sonic speed. The implications of this statement on design for low sonic-speed drag are manifold: for example, the term " interference drag " ceases to have any significance and the " isolated drag " of a wing is of little interest since it can be " cancelled " by suitably shaping the body to which it is attached.

A striking example of the efficacy of area rule is provided by some free-flight tests made to check the theoretical bases of the concept. Three non-separating models were flown (Fig. 26): the first was of a body of revolution whose shape was theoretically that to give minimum sonic wave drag for certain fixed values of length, base area, and volume (these were determined by the need to accommodate an internal rocket motor): for the second model, a wing was chosen—arbitrarily—with an untapered 50° swept plan form and biconvex sections, and to this was added a body of the same length and base area as model 'A' but so shaped that the total volume (wing + body) and the combined (wing + body) cross-sectional area distributions were identical to those of model 'A': the third model had the same gross wing as model 'B' and the same values of length, base area, and total volume as 'A' and 'B', but the body shape was such that the wave drag of the body alone was a minimum at sonic speeds. That is to say: if the *component* drags of 'B' or 'C' are considered, the wing drags are equal, but the body drag of 'C' is less than that of 'B'.

According to area rule, however, the sonic wave drags of 'A' and 'B' should be equal and less than that of 'C'. The trends indicated by the theory are closely confirmed by the experimental drag curves. (Fig. 27).

These results demonstrate also that drag tests on components of specific aircraft designs may be valueless and that the only reliable test is one on a complete model of the aircraft. This can be done using the separating-model technique. An added advantage of flying a complete model is that engine intake and ducting can be simulated: the internal dimensions of the duct are usually chosen to give a choking entry Mach number appropriate to some "average" engine and flight condition. In this way the effects of the inlet shock wave on the surrounding surfaces may be more or less correctly simulated. (Fig. 28).

Although the area rule has revolutionised the approach to the overall design of low-drag wing and body combinations, it does not absolve the designer from his responsibility for good detail design: apart from anything else the area rule takes no account of viscous phenomena. An example of the need for good detail design is the shaping of a cockpit-canopy windscreen to achieve a suitable compromise between good vision and low drag. To measure the effect of such minor variations in free flight, a simple airborne balance has been devised* which records the drag of the component in question directly. In the investigation illustrated in Fig. 29, the aim was to measure the variation of windscreen drag with angle of slope and vee. To do this, two identical canopies are mounted on a rigid box structure which is attached to the main body of the test vehicle by leaf springs. In flight, the box with its canopies and associated fairings is able to move axially relative to the main body and the amount of the movement (*i.e.* the drag) is measured by a variable-inductance pick-up (Figs. 30 and 31). The maximum axial deflection is only 0·01 in. and the natural

*A recent proposal for the estimation of wave drag supersonically makes use of the concept of an " isolated wing drag." If this is adopted, then it may be desirable to restart the measurement of wing drag in the supersonic regime.

*The design and development of this unit is due to C. Kell, of Aerodynamics Department, R.A.E.

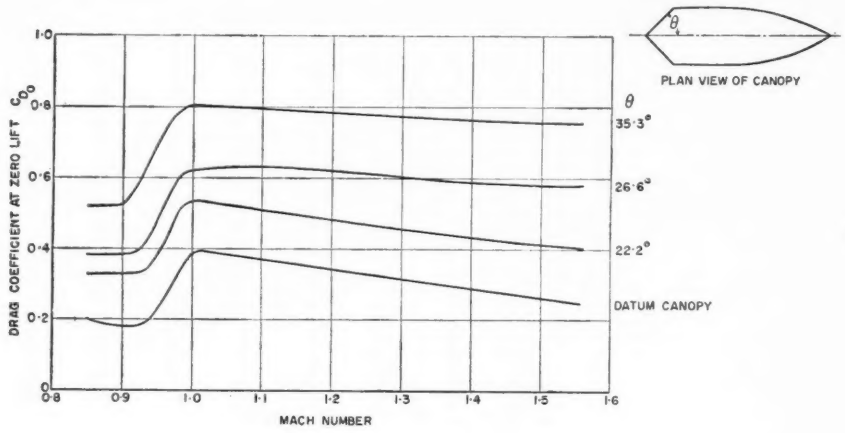


FIGURE 29. The drag of cockpit canopies with vee windscreens.

frequency of the spring system is sufficiently high to eliminate the need for internal damping. A correction has to be made for inertia effects owing to the deceleration of the test vehicle but these are small. Two canopies are used in order to allow cancellation of normal forces.

4.3. LONGITUDINAL STABILITY

The study of longitudinal stability at subsonic speeds in the tunnel and in full-scale flight testing has been to a great degree the study of the static stability parameter $\partial C_m/\partial C_L$: derived in the tunnel from measurements of moment at discrete steps of lift, and in flight from the measurement of elevator angles to trim, stick force per g, etc. to give the various stability criteria suggested by Gates and Lyon[4]—static margin, manoeuvre margin, c.g. margin. None of these methods is suitable for the assessment of longitudinal stability using free-flight models whose short time of flight and rapid variation in speed call for some transient technique. The method almost exclusively used is to excite the short-period longitudinal motion by a suddenly applied disturbance. Inevitably the ensuing motion is a mixture of the short-period and long-period (phugoid) motions but with a little ingenuity in analysis the phugoid component of the resultant oscillation can be eliminated. This transfer from static to dynamic evaluation of longitudinal stability has coincided with a resurgence of interest in dynamic stability, brought about by the rapid changes which occur at transonic speeds on most aircraft layouts and by the extremes in the values of the oscillatory derivatives occurring at all speeds with extremes in wing plan form.

From a typical short-period oscillation the following quantities may be deduced: (Appendix II)

$z_w \approx -\frac{1}{2}\frac{\partial C_L}{\partial \alpha}$	from measurements of normal acceleration and incidence or from angular acceleration
$m_w = \frac{1}{2}\frac{\partial C_m}{\partial \alpha}$	from measurement of the frequency of the oscillation
hence $m_w/z_w = -\frac{\partial C_m}{\partial C_L}$	
alternatively C_m and C_L	from measurements of normal and angular acceleration
giving C_{m_0} and $\frac{\partial C_m}{\partial C_L}$	
total damping $z_w + (m_q + m_{\dot{w}})$	from the logarithmic decrement
and hence $(m_q + m_{\dot{w}})$	the rotary damping
if the disturbance is initiated by a control $\frac{\Delta C_L}{\Delta \eta}$.	

The drag due to lift can be measured if a longitudinal accelerometer is added to the instruments needed for stability and control evaluation.

The study of these quantities in free flight is based on the theory of "quasi-steady" derivatives and the further assumption is made that the equations of motion may be considered linear *i.e.* that second, and higher order derivatives can be ignored. Of these assumptions, the first may be invalidated in the transonic region but the experimental limitations of the technique are such that a more rigorous theory would not be justified. Fortunately the design of most dynamic-stability models is such that the reduced-frequency parameter ($\omega\bar{c}/V$) of the model test is of the same order as that occurring in full-scale flight; thus the assumption of quasi-steady derivatives should have no serious influence on the process of interpreting model results in terms of full-scale behaviour. The major argument in justification of the assumption of linearity is the limitation of maximum incidence in most routine free-flight stability studies to less than 10° and frequently to less than 5°. The presence of non-linearities can be detected from a $C_m - C_L$ plot.

Whatever may be the influence of these assumptions, there is clearly an advantage in keeping to a minimum the Mach number interval covered by one complete disturbance. This raises a conflict of requirements because some of the derivatives, in particular those

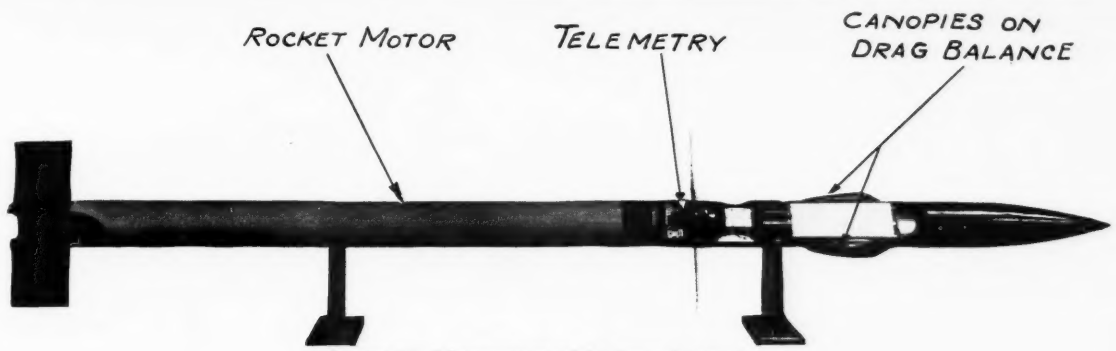


FIGURE 30. Measurement of the drag of excrescences.

involving measurement of logarithmic decrement, need three or four complete cycles for satisfactory evaluation. A suitable compromise between Mach number interval and number of cycles is obtained by flying the model with a much larger manoeuvre margin than is usual in full-scale flight ($0{\cdot}4-0{\cdot}6\bar{c}$ compared with $0{\cdot}1\bar{c}$): thus, with a longitudinal deceleration of about $5g$ in supersonic flight, the aim would be to design a model with a pitching frequency of 14 or 15 cycles/sec. associated with a time interval between disturbances of $0{\cdot}3-0{\cdot}5$ sec. and a Mach number interval of $0{\cdot}04-0{\cdot}05$. Again the greatest uncertainty arises in the region $0{\cdot}96<M<1{\cdot}00$ where the derivatives may change rapidly with Mach number. However, if a sudden deterioration in, say, damping, occurs between two control pulses this is usually visible, although there may be insufficient data to evaluate the derivative at that point. If the variation is significant a repeat model can be flown with a low drag/weight ratio and hence a lower deceleration in the critical region.

The non-representative manoeuvre margin, which is forced upon the free-flight model by these considerations, has two important repercussions on the interpretation of the model results in terms of full-scale flight behaviour. The first is the fact already noted that the frequency parameter in the model test is brought to a value much nearer to that appropriate to full-scale flight (c.0·1) than it would have been with the correct manoeuvre margin;* additionally the variation in manoeuvre margin and hence in frequency parameter is relatively small between subsonic and supersonic speeds. Unfortunately the large manoeuvre margin also implies that the model aircraft is oscillating about a much more forward axis position than its full-scale counterpart. The derivative most greatly affected by this discrepancy is the damping derivative $m_{\dot{w}}$ which has theoretically a quadratic variation with axis position. (Fig. 32). However, for most plan forms at subsonic and supersonic speeds the variation is sufficiently small to allow reasonable conversion from model to full scale, making use of the theoretical values. At near-sonic speeds interpretation is not so easy since the theoretical treatment breaks down* and the effects of shock wave/boundary layer interaction may be the predominant factor in determining changes in the damping. In this region one has no alternative at present but to apply the model results without correction. A possible solution is to fly models with different axis positions but the available range of positions is limited and is usually too small to produce appreciable differences in the values of the derivatives.

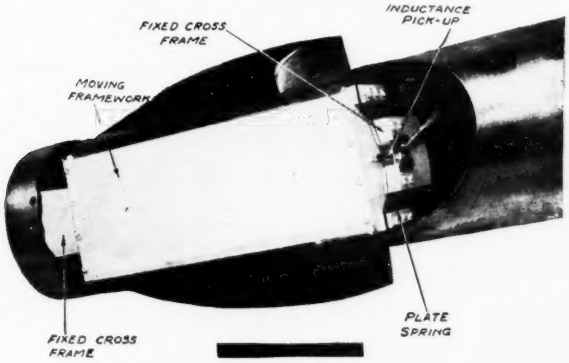


FIGURE 31. Airborne drag balance.

*Because the coefficients μ_1 and i_B are invariably greater for the model than they are for the full-scale aircraft.

Of course, the damping behaviour is not determined by $m_{\dot{w}}$ alone but by the total damping derivative $z_w+(m_q+m_{\dot{w}})/i_B$ and a large error in $m_{\dot{w}}$ may, therefore, have little influence on the total damping. Another point that arises from this expression is the influence of the inertia term $i_B=g_B/W\bar{c}^2$. The model value for i_B is usually two or three times the full-scale value and hence, other differences apart, the model *total* damping will differ from that of the full-scale aircraft. More significantly, if the rotary damping term $(m_q+m_{\dot{w}})$ becomes positive it is possible for the model oscillations to be damped when those of the full-scale aircraft would be divergent. This fact is convenient in model experiments when designs having low damping have to be investigated but it removes a possible grain of comfort from the designer! The difference in model and full-scale behaviour owing to differences in i_B is entirely one of flight mechanics and the conversion, model scale-

*The limitations in the subsonic theory confine its validity to $M<0{\cdot}8$ and those in the supersonic theory confine it to $M>1{\cdot}2$. Mangler has produced a theory by which $m_{\dot{w}}$ can be evaluated at $M=1{\cdot}00$ but, like the supersonic and subsonic theories, this takes no account of shock wave or viscous effects.

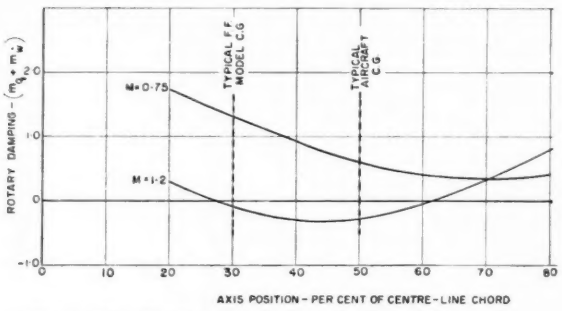


FIGURE 32. The theoretical effect of axis position on the longitudinal damping of a delta wing of aspect ratio 4.

full scale, is not, therefore, open to the doubts which arise from differences in axis position.

These limitations, set by the need to make best use of the analysis technique with the instruments available and to limit the unknowns in extending the model results to full scale, place obvious difficulties in the way of the designer of dynamic-stability models but with the accumulated experience of the past few years a design procedure has been evolved which covers most requirements. Dynamic-stability models fall into two main groups depending on the method of inducing the short-period oscillation. The simpler method is to install small cordite rockets in the model, thrusting at right angles to the X-Y plane. These are discharged at predetermined intervals throughout the coasting flight of the model by a timing unit. (Figs. 33 and 34). The second method is to disturb the model by means of an aerodynamic control, either an all-moving tailplane or a trailing edge flap. (Fig. 35).

Although much simpler to manufacture, the rocket-disturbed models suffer from several disadvantages. For example, the number of disturbances per flight is limited by the space available for rockets and is usually much smaller than for an actuated control model; the maximum amplitude of the disturbance is limited by the impulse of the rocket and may vary between different disturbances because of differing rocket positions and oscillation frequencies; no measure of control effectiveness can be obtained. In spite of these drawbacks the method is still most valuable for a quick preliminary assessment of dynamic stability.

The bulk of dynamic-stability testing now falls to the actuated control model and here, as in all free-flight work, the essence of success is simplicity. This applies particularly to the control-actuating system which is a pneumatically operated one using well-tried components developed by both the missile and aircraft groups. The controls are usually deflected in a square-wave pattern—this is simple to generate—the frequency of the square wave being determined by an electro-mechanical clock and selector valve. (Figs. 35 and 36). Stressing requirements for stability models can be severe: even with an incidence limitation of $\pm 5°$, normal accelerations at the c.g. of $\pm 20g$ are usual and the longitudinal and lateral loads during the boost phase may be more severe than this. As a result light alloy construction is almost inevitable and the controls

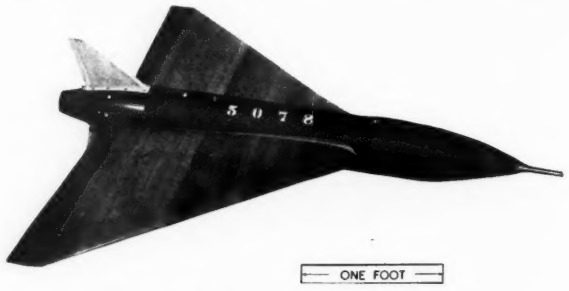


FIGURE 33. A rocket-disturbed longitudinal stability model.

are usually manufactured from high tensile steel to avoid spurious effects owing to control distortion.

Typical of the results obtained from free-flight dynamic-stability tests are those illustrated in Figs. 37-39. The disadvantage of the small number of disturbances given by the rocket-disturbance technique was overcome in the example quoted by flying two models: this was quicker than building a single actuated control model. Even so, the superiority of the actuated control technique is obvious from Fig. 39. These results exemplify one of the most cogent reasons for free-flight work, the investigation of rapidly varying derivatives in regions where the restraints and low Reynolds numbers associated with wind-tunnel testing may be at their most misleading.

4.4. MEASUREMENT OF DRAG AT LIFT

The accuracy with which the drag at lift may be measured is dictated to a great degree by the limitations set by model stresses and available instrument ranges. Thus for most pitching models a limit of $\pm 30g$ is set for normal acceleration at the c.g. (this may imply $\pm 60g$ at the tail), and the minimum range of suitable longitudinal accelerometers so far available is 0-5g. For a typical model these limits yield uncertainties of the order of ± 10 per cent. in total drag at $M = 1{\cdot}0$ and ± 20 per cent. at $M = 2{\cdot}0$. These uncertainties can be reduced if the model is flown at high altitude where a higher lift

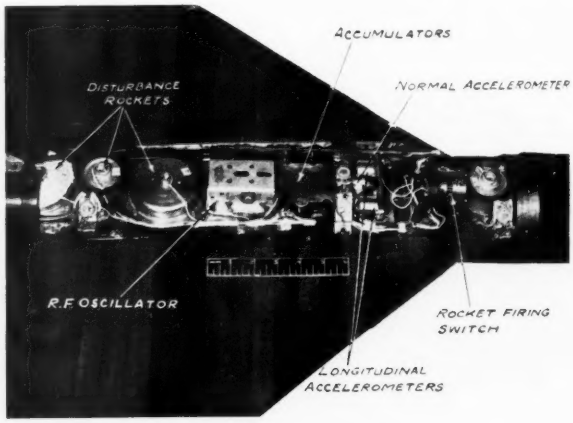


FIGURE 34. Interior of rocket-disturbed stability model.

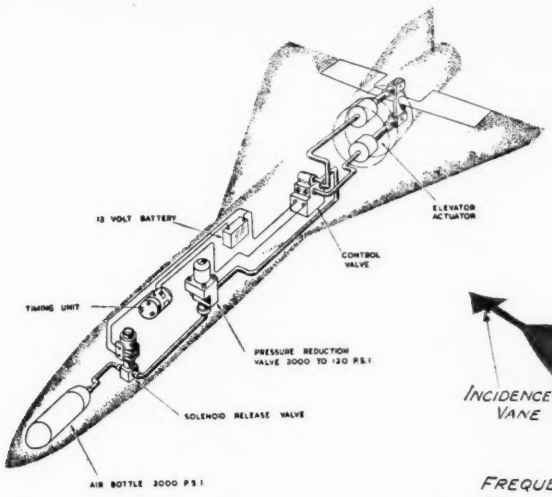


FIGURE 36. Control actuation system.

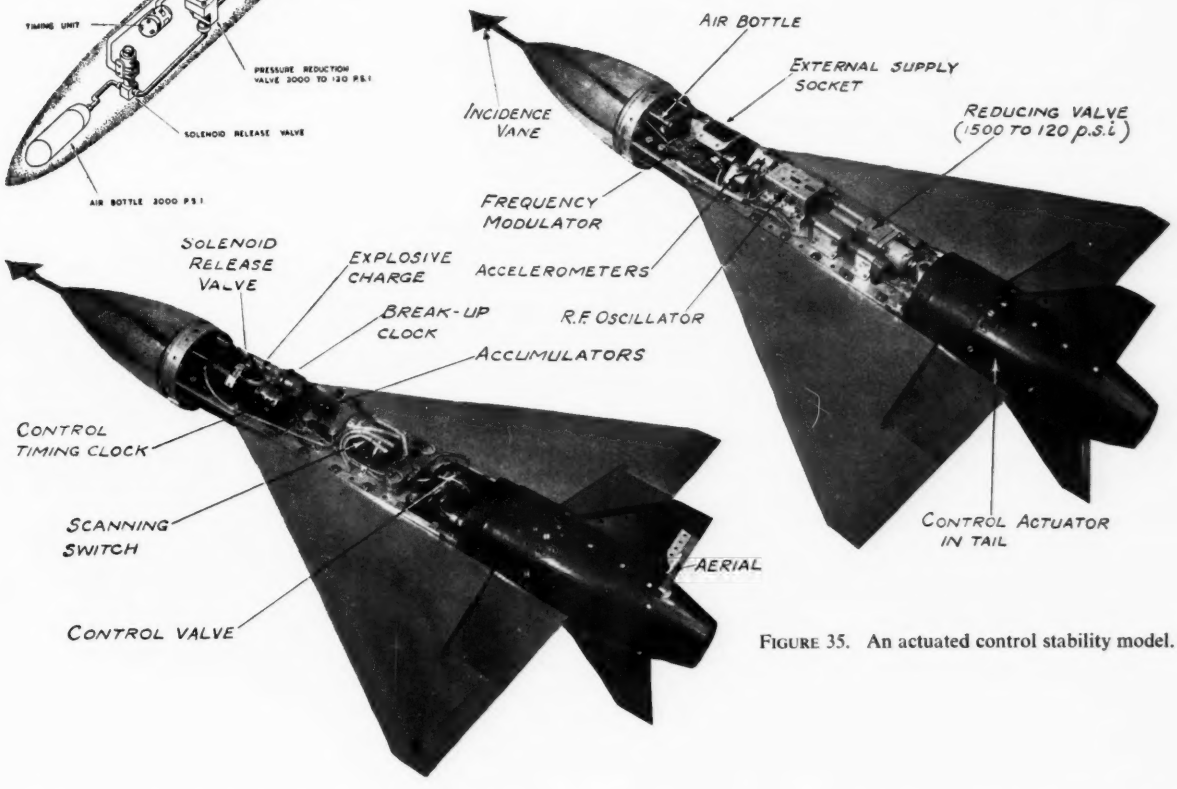


FIGURE 35. An actuated control stability model.

coefficient may be obtained with the same limitation in normal acceleration.

An additional pitfall exists in the interpretation of drag-at-lift records when the induced drag is that corresponding to zero leading-edge suction *i.e.** $C_{D\,(\text{induced})} = C_L \sin \alpha$. This arises from the fact that the longitudinal accelerometer records a component of lift as well as drag, namely,

$$C_c = C_{D_0} + C_{Di} - C_L \sin \alpha$$

where

$$C_c = f \frac{W}{\frac{1}{2}\rho V^2 S}$$

this may be written

$$C_c = C_{D_0} + C_{Di} - C_L \sin \alpha$$

and it is clear from this expression that when $C_{Di} = C_L \sin \alpha$ there will be no oscillation on the longitudinal-accelerometer record when the model is pitching. But lack of response may be simply a result of insufficient accelerometer sensitivity and this, if misinterpreted, may in turn lead to a pessimistic induced drag result.

One possible means of improving the accuracy of induced drag measurement is to measure the forces on the wing directly by means of some form of internal balance after the fashion of that already developed for cockpit canopies (*see* Section 4.2).

4.5. PRESSURE MEASUREMENTS

One of the disadvantages of the free-flight technique is its inability to present a physical picture of the flow conditions causing various peculiarities in overall behaviour. Some way can be gone towards eliminating this disadvantage by means of pressure-distribution measurements. An obvious limitation to such a procedure is set by the relatively small number of telemetry channels available but a certain amount of information has been obtained on wing-flow phenomena and on the

*For notation *see* Appendix.

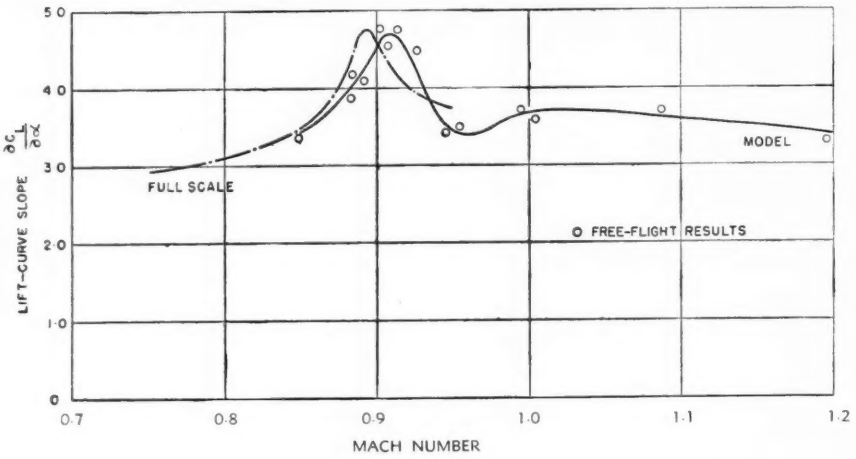


FIGURE 37. Comparison between full-scale and free-flight model measurements of lift curve slope.

effects of the boundary layer on body pressure distribution. (Fig. 40).

The pressure recovery of various engine intake configurations also falls within this category although, because of the relatively restricted range of operating conditions which can be covered, these have tended to be no more than high Reynolds number checks on tunnel investigations. This can be of importance when the performance of the intake is likely to be seriously affected by shock-induced boundary layer separation.

4.6. AEROELASTICITY

Evidence from the initial control effectiveness tests on fixed deflection controls showed clearly that distortion of the wings was a significant factor particularly with wooden wings at supersonic speeds. A limited investigation was made with rectangular wings manufactured from compressed wood, light alloy and steel and this confirmed that the order of the aeroelastic effect was reasonably well predicted by the theory of Broadbent[5] (Fig. 41). To apply this requires a knowledge of the torsional characteristics of the wing, and a simple test rig was constructed to obtain the torsional stiffness parameter θ_m (wing twist/unit torque) and the locus of flexural points for every control wing flown. Torsion is applied by a pure couple at the tip and the resulting shape of the wing measured by a series of dial gauges. (Fig. 42).

The investigation of aeroelasticity by free-flight models is still in its infancy*. As with much free-flight work the determination of the end product is not too difficult: the difficulty is to obtain enough information to explain away the inevitable differences which arise between theory and experiment. To do this calls for a knowledge of the shape of the distorted elements in flight and possibly a knowledge of the corresponding aerodynamic loading. Some progress has been achieved towards the measurement of distortions in flight by using strain gauges but it is too early to comment on the success or otherwise of such a scheme.

4.7. SONIC BANGS

The loud noises which accompany a body flying at supersonic speeds gave rise to a plethora of explanation and speculation when full-scale aircraft first started to exceed the speed of sound. The rocket test vehicles employed in free-flight experiments have proved to be a useful means of collecting quantitative information on this subject since they produce bangs of measurable intensity under carefully recorded conditions of flight.

Although there is still some doubt about the precise manner in which bang intensity depends upon such things as aircraft size, altitude, height, acceleration, and

*This statement does not apply to flutter investigations which have been in progress for some time.

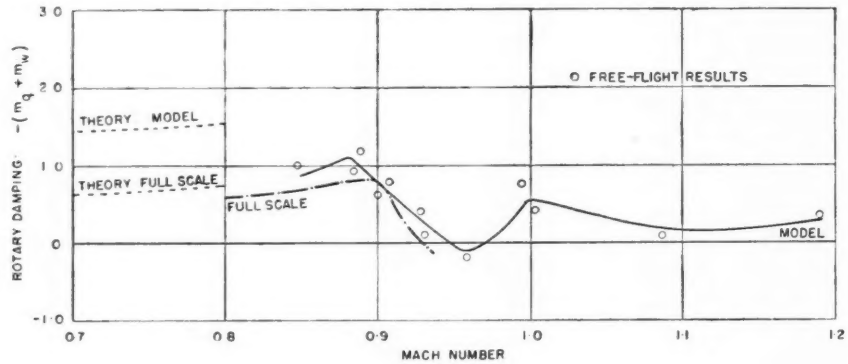
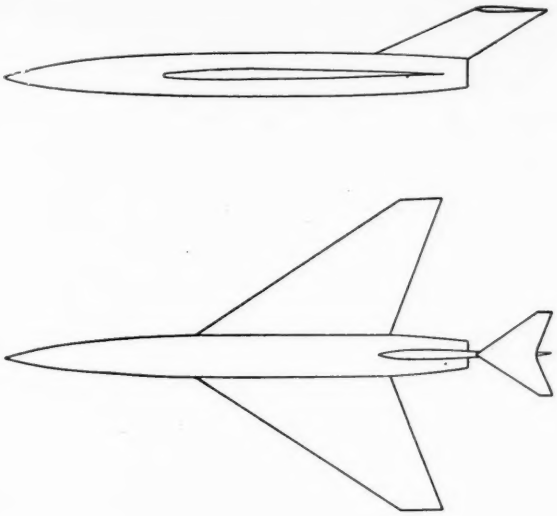
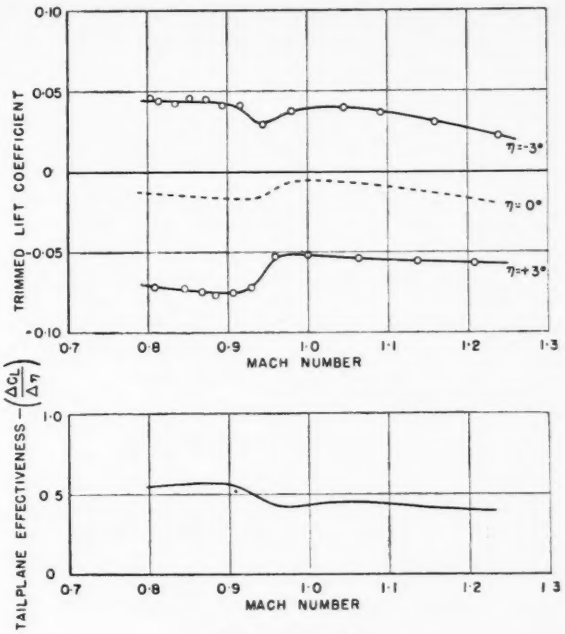


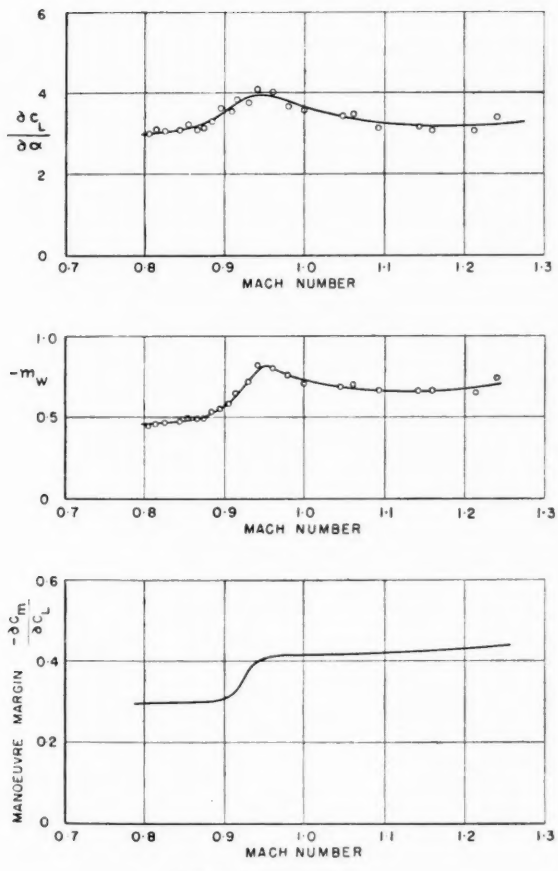
FIGURE 38. Comparison between full-scale and free-flight model damping measurements.



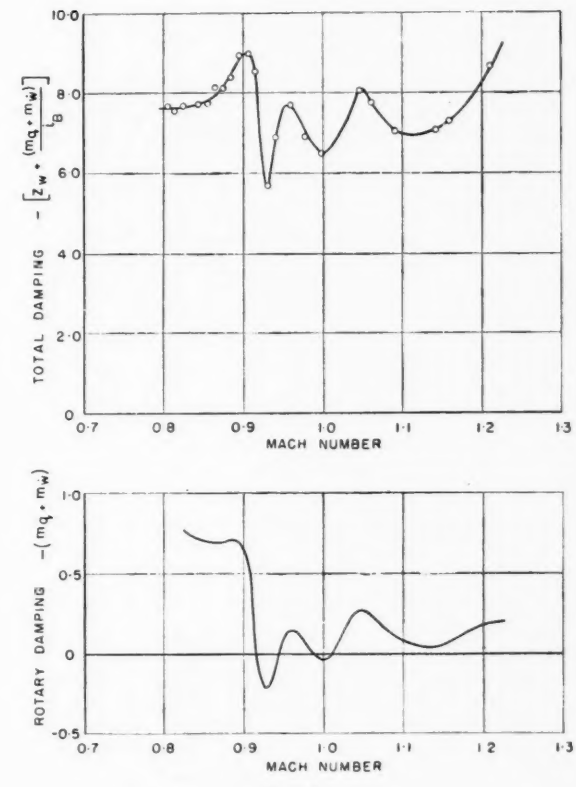
WING SPAN 2·43 ft.
WEIGHT 35 lb.



Tailplane effectiveness



Lift and static stability



Damping

FIGURE 39. Stability results from an actuated-control model.

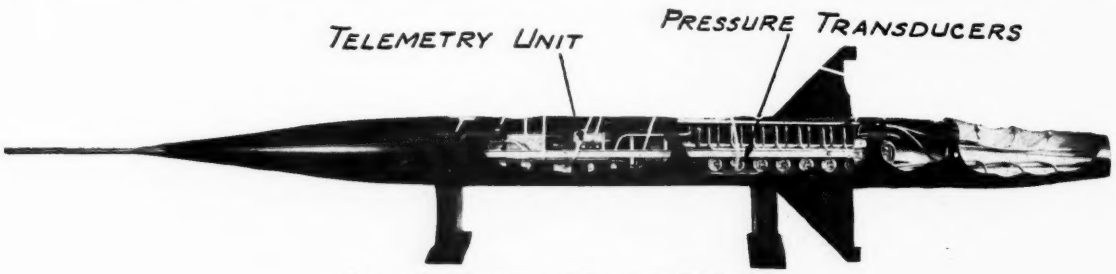


FIGURE 40. Measurement of pressure distribution.

so on, the basic tenet on the conditions for the occurrence of a sonic bang is now accepted, *i.e.* that a bang is "created" when the velocity component of the vehicle towards the observer is sonic. This fact provides an explanation of the three bang record illustrated in Fig. 43, which was obtained from a separating test vehicle with a maximum Mach number of about 2·0. The first bang created occurs soon after the unseparated test vehicle has reached sonic velocity: the angle subtended by the flight path and the observer,—vehicle line is then small. Because the vehicle is far away and has a large longitudinal acceleration the bang is relatively weak. The second—and third—created bangs occur after the rocket and dart have separated and are decelerating: these are of greater intensity because the decelerations and distances are relatively small (Fig. 43).

5. Future Developments

A great deal of the work done so far in free flight has been concentrated on the transonic region but currently, Mach numbers of 2·5 to 3·0 are in use. The extension to higher Mach numbers involves no revolution in technique though it does call for some ingenuity in the development of efficient boost systems.

One of the most interesting contemporary problems of flight at high supersonic speed is that of heat transfer and its effects on aircraft performance and structure. Development work has started on techniques to investigate heat transfer problems in free flight: preliminary indications are that, in spite of instrument and interpretation difficulties associated with the rapid changes in flight velocity, the free-flight technique will be able to contribute greatly in this field. Closely associated with heat-transfer measurement is the problem of detecting the state of the boundary layer: it is possible to go some way towards the solution of this problem by the use of static and Pitot comb pressure measurements, but these are limited in scope and application, and the development of more elegant methods is one of the primary tasks now in hand.

So far as stability is concerned there is no inherent reason why the methods which have been applied to the investigation of longitudinal stability should not be applied with equal success to the lateral motion, with the proviso that certain limits in model design and flight plan are imposed to avoid undue complication of the analysis from roll effects. These tests would still be confined to zero or small lift coefficients, and as has been made clear recently, the trends in design for supersonic aircraft have brought with them troubles which force attention on the stability in conditions of combined pitch, yaw and roll. Present indications are that the accurate quantitative recording of a combined roll-yaw-pitch motion is a formidable task but qualitative tests using simplified models on a "go" or "no go" basis look promising.

Allied to the cross-coupling problem is the investigation of aerodynamic phenomena at high incidence

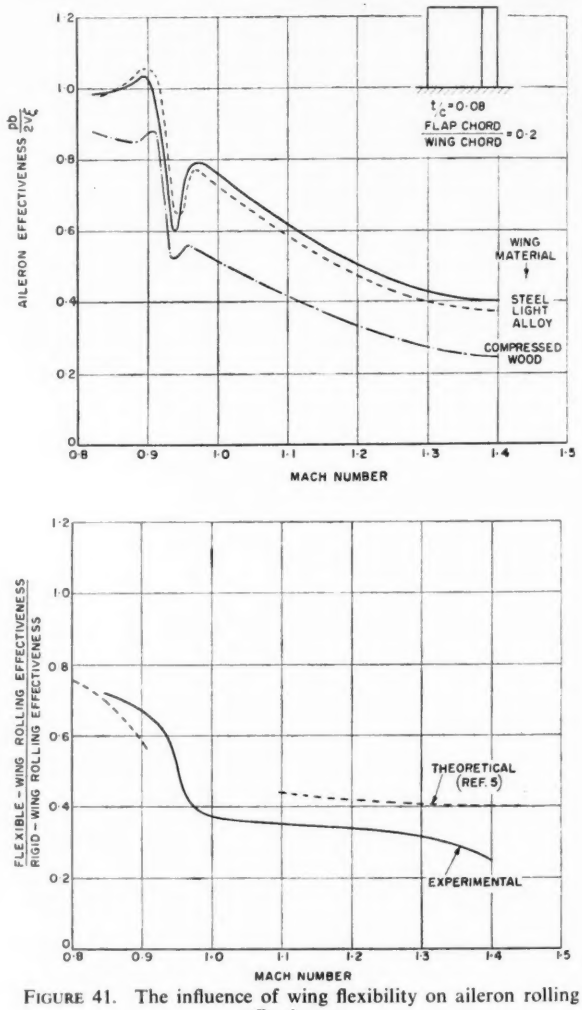


FIGURE 41. The influence of wing flexibility on aileron rolling effectiveness.

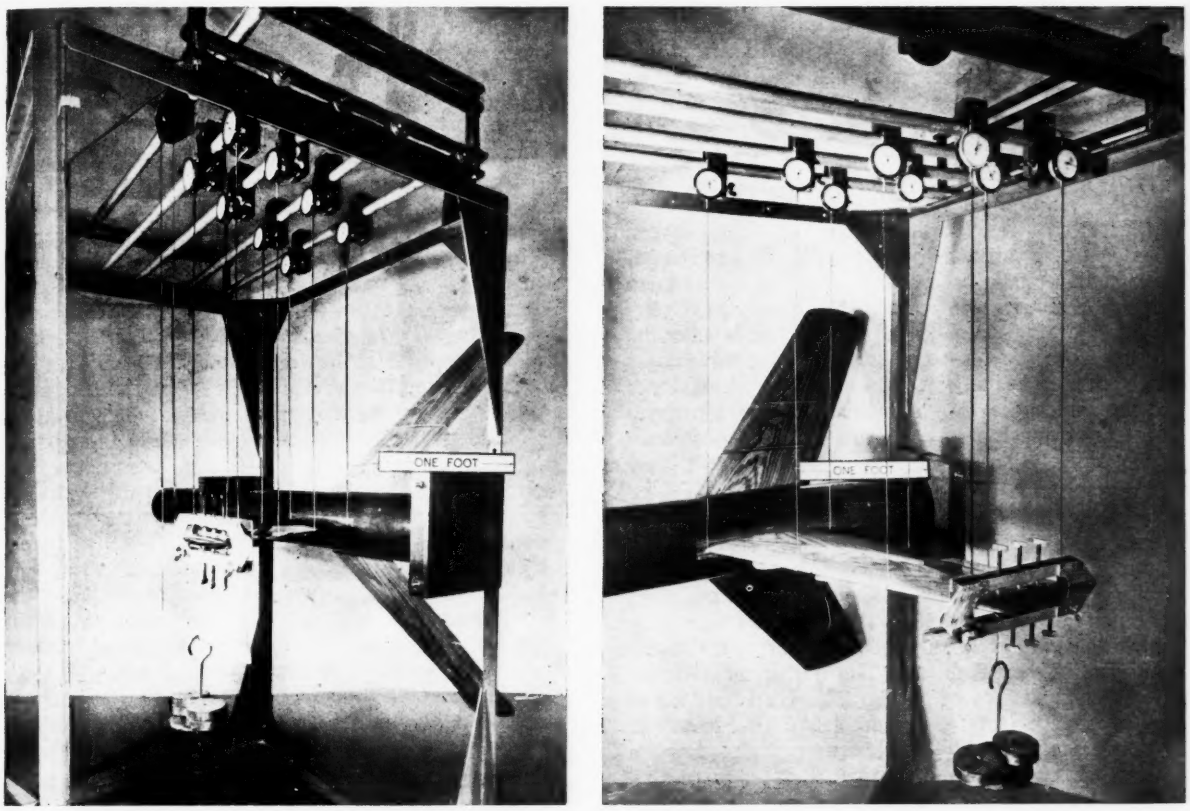


FIGURE 42. Rig for the determination of wing torsional characteristics.

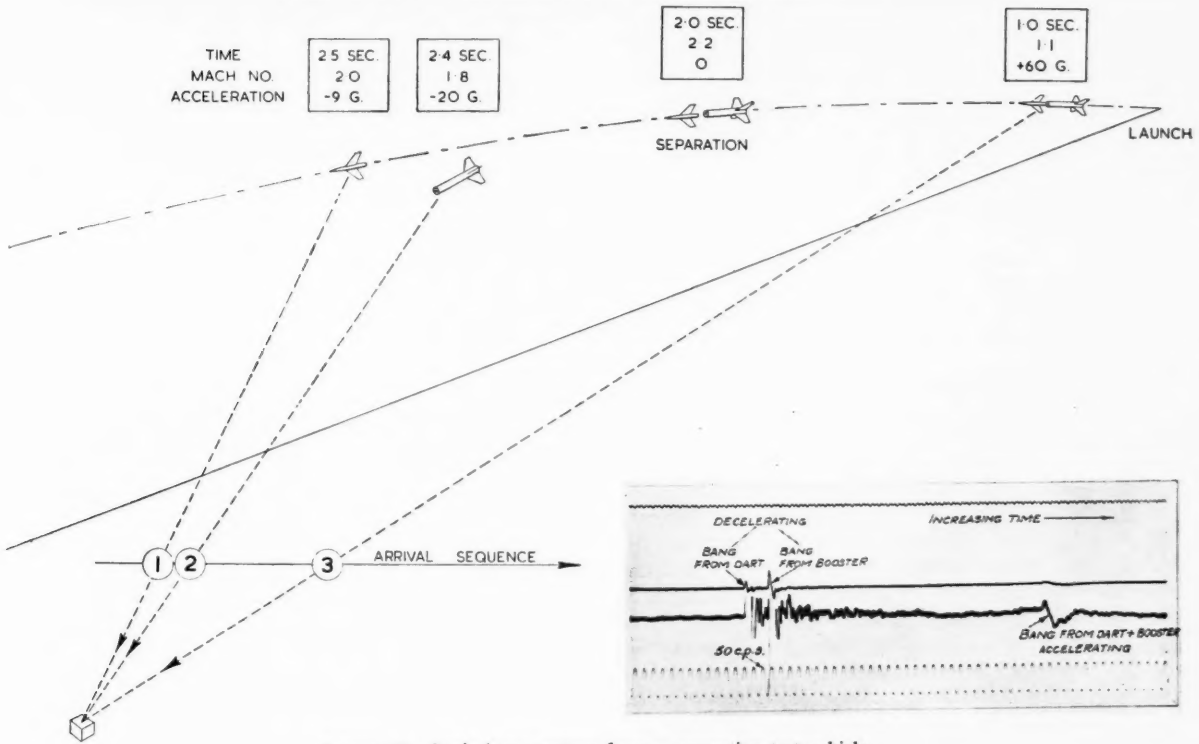
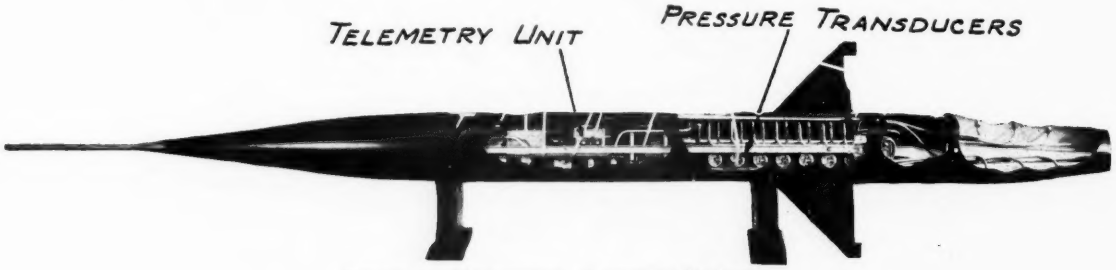


FIGURE 43. Sonic bang pattern from a separating test vehicle.



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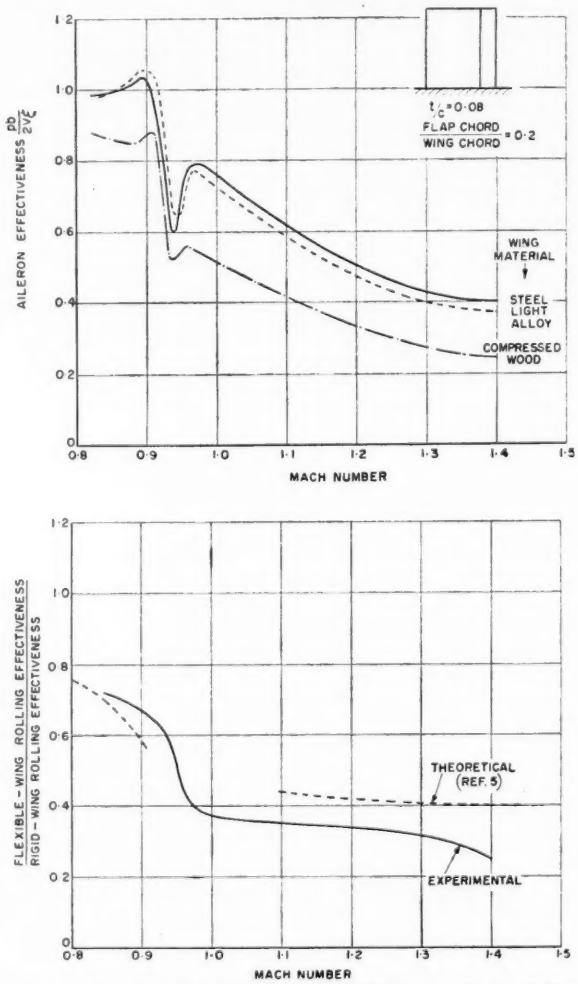

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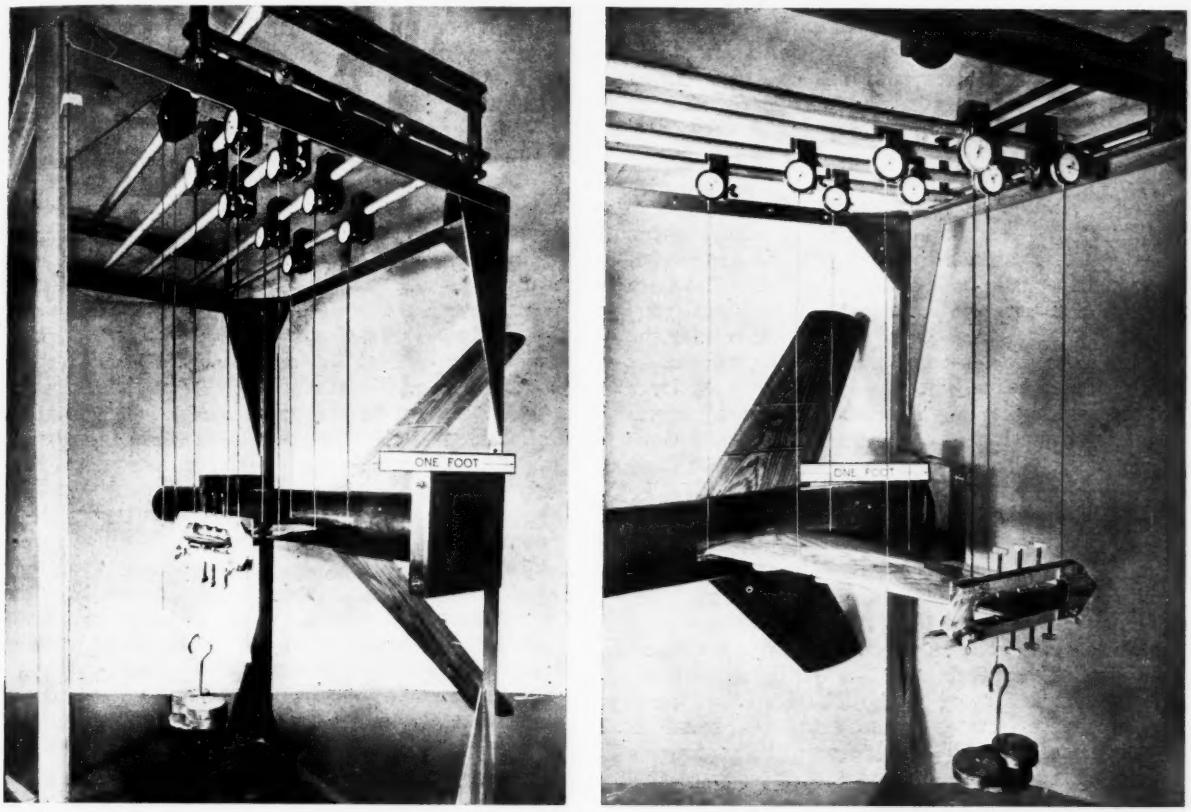

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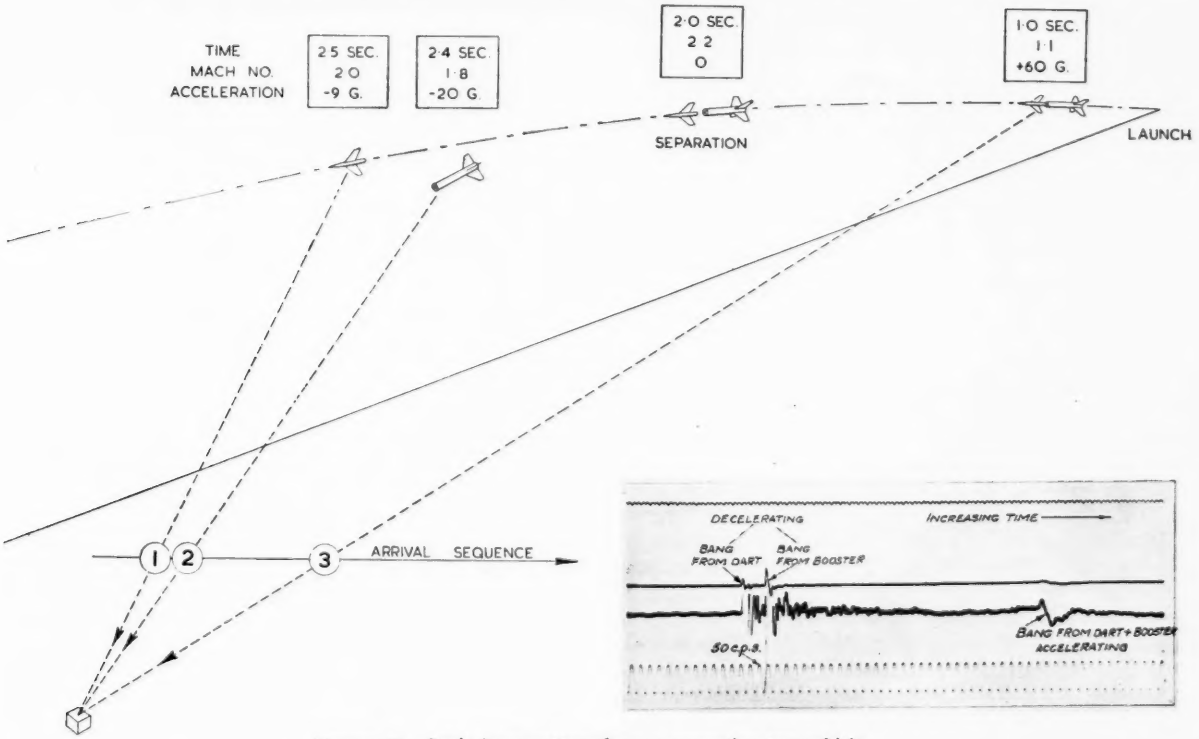

FIGURE 43. Sonic bang pattern from a separating test vehicle.

($\alpha > 10°$) particularly those phenomena associated with vortex flows. The difficulty here arises from the high model loadings associated with high incidence tests at sea level: such tests may have to be confined to higher altitudes than those at present in use.

6. Some General Thoughts on the Technique

There are two conditions, among many others, which must be satisfied by an experimental method if its continuance is to be justified. The first is that there must be no serious impediment to the correct interpretation of the results and the second is that the method must provide some advantage or advantages which cannot be provided by alternative techniques however much they are improved. These considerations are obviously relevant to the free-flight technique at the present time.

In the section on dynamic stability the problem of interpreting the results in terms of full-scale flight behaviour has been discussed. There are several other factors which affect the interpretation of free-flight results generally. Foremost amongst these is the effect of longitudinal deceleration. Most free-flight test vehicles have a deceleration of 5-10g during the supersonic part of their flight and 2-4g during the subsonic part. For models flying at zero lift there is nothing in the experience so far accumulated on free-flight investigations, either by specific tests or by comparison with other methods and theory, which suggests that decelerations of this order have any appreciable effect on fluid-flow phenomena. For pitching models, the evidence is scantier but again there is nothing to suggest that the flow conditions in decelerated flight differ from those in flight at constant velocity. Intuitively one feels that if discrepancies do arise they will occur in the mixed flow conditions appropriate to transonic speeds. Of course, deceleration might have no effect on flow phenomena and still have a considerable effect on the flight mechanics of dynamic stability testing. This problem has been examined by Voepel at the R.A.E. and in an unpublished paper[6] he has shown that decelerations of order appropriate to free-flight work have but a small (< 1 per cent.) effect on the evaluation of the derivatives, when the constant-speed equations of motion are applied to accelerated flight.

A more specific problem, already mentioned, is that of assessing the state of the boundary layer in free-flight experiments. The Reynolds numbers involved are much higher than are usual in the wind-tunnel ($R = 7 \times 10^6$ per ft. at $M = 1{\cdot}0$) and for large scale models they approach those of the full-scale aircraft flying at high altitude: one is tempted, therefore, to assume that the boundary layer and skin friction effects are similar. For transonic speeds this assumption may not be greatly in error—although it ignores surface finish effects—but as flight speeds approach Mach numbers of 2·0 and above, incorrect representation of heat transfer effects among other things will cast doubts on its validity.

With the exercise of ingenuity such problems will be overcome or circumvented in time, but this still leaves the more general issue of whether or not free-flight testing can justifiably be continued when large transonic and supersonic tunnels are now available. The wind tunnel is in many respects a much more satisfactory facility than is the free-flight technique: the operation of a tunnel is much less risky and inconvenient than a free-flight test; a wider range of parameter can be investigated and in much more detail; the *causes* of various aerodynamic phenomena can be more readily investigated by various flow visualisation techniques; repeat tests on doubtful results can be made quickly and easily.

These appear to be formidable arguments for the complete abandonment of free-flight tests but there are equally strong counter arguments. For example, although great advances have been made in reducing wall interference in transonic tunnels, it would be presumptuous at this stage to assume that it can be eliminated completely. Allied to this are the problems raised by the distortions necessary in some tunnel models to accommodate supports and measuring equipment. This difficulty is made more serious by the high fineness-ratio bodies typical of supersonic aircraft; with a limitation on length set by the tunnel working section, appreciable distortions may be necessary. With low fineness ratio bodies distortion may still occur because of the need to avoid blockage effects. In free flight these disadvantages are eliminated completely.

There is no rigid upper limit to the maximum Mach number which can be achieved in free flight and the Reynolds numbers are sufficiently near full scale to eliminate most of the doubts which usually arise when tunnel results have to be interpreted in terms of full-scale behaviour. Capital cost and availability of power set a fairly well defined limit to the combined maximum Reynolds number and Mach number which can be attained by a wind tunnel, and once any specific tunnel has been constructed, even relatively small increases in maximum Mach number may involve extensive modifications.

Dynamic stability work in the tunnel, at transonic and supersonic speeds is still in a rudimentary state. In spite of the ingenuity shown by designers of dynamic stability equipment for the tunnel, the very nature of such tests implies that the constraints imposed by the test rig and the tunnel may introduce more serious errors than in the corresponding static tests. In addition there are certain dynamic stability experiments, *e.g.* those associated with inertial cross-coupling at high rates of roll, which can only be done in free flight.

Finally, there is the question of the time taken to obtain results by the two techniques. For many investigations the principal factor in deciding this is the time required for model design and construction. Considering models designed to give comparable amounts of information, *e.g.* lift, drag and moment tunnel models, and dynamic stability free-flight models there appears to be little difference in the design and manufacturing time. But for investigations where information is needed at zero-lift only, *e.g.* drag, intake efficiency, the free-flight test can produce an accurate

and representative answer in as little as one quarter of the time required to do the corresponding tunnel test.

These arguments serve to show that the tunnel and free-flight techniques are complementary, and not mutually exclusive. For detailed examination of static forces and moments, for the investigation of problems requiring flow visualisation and for a great many basic research experiments as opposed to tests on specific designs, the wind tunnel is unchallengeably the superior technique. The function of free-flight testing is to obtain the limited amount of information necessary to provide a correct frame of reference for the tunnel results, to make checks on those problems where the attainment of high Reynolds number is an essential for correct flow representation, and to act as extension to the tunnel when results are required at Mach numbers beyond the tunnel limits.

ACKNOWLEDGMENTS

The successful development of any new technique in these complicated times usually involves the work of many hands: and so it is with the work described here. To the many individuals and groups whose contributions have provided the material for this paper, the authors wish to express their indebtedness.

All the illustrations are Crown Copyright.

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Notation

$\bar{c}$ standard mean chord
b wing span
S wing area
d axial distance between normal accelerometers
D distance from c.g. to focal point
W weight
A moment of inertia about the longitudinal axis
B moment of inertia about the lateral axis
$\mu_1 = W/(g\rho S\bar{c})$
$t = \mu_1 \bar{c}/V$
$i_B = gB/(W\bar{c}^2)$
V flight-path velocity
n normal acceleration in terms of g
f longitudinal acceleration
$C_L = W(n\cos\alpha - f\sin\alpha)/(\frac{1}{2}\rho V^2 S)$
$C_D = W(f\cos\alpha + n\sin\alpha)/(\frac{1}{2}\rho V^2 S)$
$C_m = M/(\frac{1}{2}\rho V^2 S\bar{c})$
α angle of incidence
$\Delta\alpha = \alpha - \alpha_{trim}$
w normal velocity
q angular velocity in pitch
p angular velocity in roll
$\bar{p}$ steady-state angular velocity in roll
$\dot{p}$ angular acceleration in roll
ξ aileron angle
η tailplane / elevator } angle
Z normal force
M pitching moment
L rolling moment

Z_w, M_w, L_p, etc. $= \dfrac{\partial Z}{\partial w}$, $\dfrac{\partial M}{\partial w}$, $\dfrac{\partial L}{\partial p}$ etc.

$l_\xi = 2L_\xi/(S\rho V^2 b)$
$l_p = 4L_p/(S\rho V b^2)$
$z_w = Z_w/(S\rho V)$
$z_\eta = Z_\eta/(S\rho V^2)$
$m_q = M_q/(S\rho V\bar{c}^2)$
$m_w = M_w/(S\rho V\bar{c})$
$m_{\dot{w}} = M_{\dot{w}}/(S\rho V\bar{c}^2)$
$m_\eta = M_\eta/(S\rho V^2\bar{c})$
t time: wing thickness
t_0 an arbitrary time of origin in the dynamic stability analysis
t_p time to peak of normal acceleration
ω natural frequency of short-period longitudinal oscillation (rads./sec.)
ω_n undamped natural frequency $= \sqrt{(\omega^2 + \lambda^2)}$
λ damping factor
ν reduced frequency $= \omega\bar{c}/V$
δ, ϕ phase angles
ρ atmospheric density

APPENDIX I

Details of the Analysis Procedures used to Obtain Roll Derivatives

Rolling Effectiveness using Fixed-Deflection Controls

The quantity to be evaluated is $\dfrac{\bar{p}\,b}{2V\xi}$ where $\bar{p}$ is the steady rate of roll corresponding to deflection ξ and speed V.

The measured rate of roll p is a transient value since the test vehicle usually has finite acceleration in roll throughout its flight.

p and $\bar{p}$ are connected by the equations

$$L_\xi \xi + L_p p = A\,\dot{p} \quad . \quad . \quad . \quad (1)$$

$$L_\xi \xi + L_p \bar{p} = 0$$

so that

$$\bar{p} = p - \frac{A}{L_p}\dot{p}.$$

A is obtained by swinging the vehicle prior to test.
L_p is estimated or measured in free-flight.
$\dot{p}$ is derived from the rate-of-roll measurement.

Rolling Effectiveness using Actuated Controls

As in equation (1) the equation of motion in roll is

$$A\,\dot{p} - L_p p = L_\xi \xi$$

or in non-dimensional form.

$$\dot{p} + \frac{k\rho V}{A} l_p p = \frac{m\rho V^2}{A} l_\xi \xi$$

where k and m are constants depending on the geometry of the test wing.

This may be written

$$\dot{p} = -\frac{k\rho V}{A} l_p \left(p - \frac{mV}{k} \frac{l_\xi \xi}{l_p} \right)$$

and since

$$\frac{mV}{k} \frac{l_\xi}{l_p} \xi = \frac{l_\xi}{l_p} \frac{2V}{b} \xi = \bar{p}$$

$$\dot{p} = -\frac{k\rho V}{A} l_p (p - \bar{p}).$$

Thus l_p may be evaluated from the slope of a plot of p against $\dot{p}$.

The aileron rolling power then follows from:

$$l_\xi = \frac{l_\xi}{l_p} l_p = -\frac{\bar{p} b}{2V\xi} l_p.$$

APPENDIX II

Details of the Analysis Procedures used to Obtain Pitch Derivatives

The raw information which comes from a dynamic stability flight comprises a series of oscillatory variations of normal acceleration, incidence, longitudinal acceleration, angular acceleration and control position (Fig. 44). There are several methods available for converting these quantities into derivative form: all of them are based upon the classical equations of motion but the detailed treatment varies according to the quantity and quality of the information available. The methods described here were developed specifically for the Aerodynamics Department Free-Flight Group*.

The basic equations describing the short period motion may be written

$$-\frac{z_w}{V} w + \frac{\hat{t}}{V} \dot{w} - \hat{t} q = z_\eta \eta \quad . \quad . \quad (2)$$

$$-\frac{\mu_1 m_w}{V i_B} w - \frac{\hat{t} m_{\dot{w}}}{V i_B} \dot{w} - \frac{\hat{t} m_q}{i_B} q + \hat{t}^2 \dot{q} = \frac{\mu_1 m_\eta}{i_B} \eta \quad (3)$$

*The mathematical treatment quoted in this section is due to H. M. A. Voepel, of Aerodynamics Department, R.A.E.

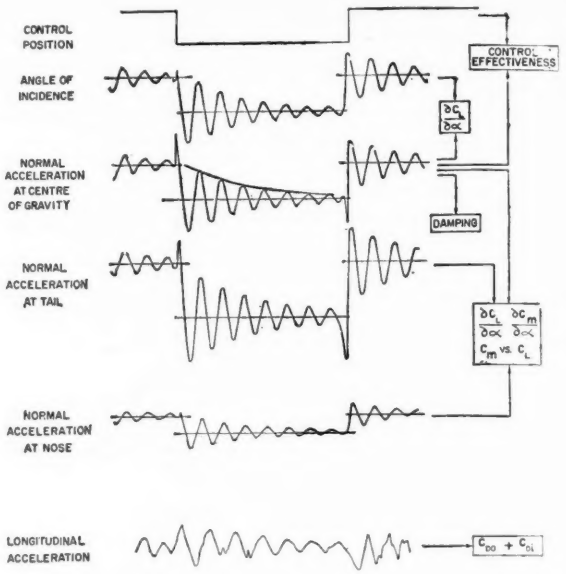

FIGURE 44. Stability, control and drag information obtained from the short period oscillation.

where

$$\mu_1 = \frac{W}{g\rho S\bar{c}}$$

$$\hat{t} = \frac{\mu_1 \bar{c}}{V}$$

$$i_B = \frac{gB}{W\bar{c}^2}$$

These equations may be written

$$-\frac{z_w}{V} w + \frac{\hat{t}}{V} \dot{w} - \hat{t} q = 0 \quad . \quad . \quad . \quad (4)$$

$$-\frac{\mu_1 m_w}{V i_B} w - \frac{\hat{t} m_{\dot{w}}}{V i_B} \dot{w} - \frac{\hat{t} m_q}{i_B} q + \hat{t}^2 \dot{q} = 0 \quad . \quad (5)$$

if the analysis is conducted with the trim values of the various parameters as origins of reference.

Combining equations (4) and (5) with the kinematic relation

$$n = \frac{1}{g} (\dot{w} - Vq)$$

gives the equation of motion in terms of normal acceleration, n

$$\hat{t}^2 \ddot{n} - \left[z_w + \frac{m_q}{i_B} + \frac{m_{\dot{w}}}{i_B} \right] \hat{t}\,\dot{n} + \left[z_w \frac{m_q}{i_B} - \mu_1 \frac{m_w}{i_B} \right] n = 0. \quad . \quad . \quad . \quad (6)$$

The longitudinal stability derivatives may then be deduced as follows.

Damping

The first stage in the damping evaluation is to plot peak normal acceleration values against peak number: if, say, the peak values below the trim acceleration are plotted with their signs reversed, the mean line between lower and upper peaks is then the mean locus of the upper and lower

peaks plotted on a true zero (Fig. 45). A logarithmic plotting of this mean line allows the damping factor λ to be determined.

From equation (6)

$$\lambda = -\frac{\left[z_w + \frac{(m_q + m_{\dot{w}})}{i_B}\right]}{2\hat{t}}$$

hence the total damping

$$-\left[z_w + \frac{(m_q + m_{\dot{w}})}{i_B}\right]$$

may be evaluated.

Now $$z_w = -\tfrac{1}{2}\left(C_D + \frac{\partial C_L}{\partial \alpha}\right) \approx -\tfrac{1}{2}\frac{\partial C_L}{\partial \alpha}$$

and $\partial C_L/\partial \alpha$ may be obtained from a plot of C_L against incidence or from the "focal point" method described below.

Knowing z_w the rotary component of the damping, $(m_q + m_{\dot{w}})$ follows.

Aerodynamic centre

The movements of the aerodynamic centre may be deduced from the manoeuvre margin, $\frac{m_w}{z_w}$.

The evaluation of z_w has been described: m_w follows from the frequency of the oscillation.

From equation (6) the undamped frequency (rads./sec.) is

$$\omega_n = \frac{1}{\hat{t}}\left[z_w \frac{m_q}{i_B} - \mu_1 \frac{m_w}{i_B}\right]^{\frac{1}{2}}$$

for most aircraft layouts

$$z_w \frac{m_q}{i_B} \ll \mu_1 \frac{m_w}{i_B}$$

and hence $$m_w = -\frac{i_B}{\mu_1}(\omega_n \hat{t})^2.$$

ω_n is given by

$$\omega_n = \sqrt{(\omega^2 + \lambda^2)}$$

where ω is the actual frequency of the oscillation.

Pitching moment

Equation (4) may be re-written

$$q\hat{t} = \left[\left(\frac{\dot{w}}{V}\right)\hat{t} - z_w\left(\frac{w}{V}\right)\right]$$

and by substitution for $q\hat{t}$ in equation (5)

$$-\frac{\mu_1 m_w}{i_B}\left(\frac{w}{V}\right) - \hat{t}\frac{m_{\dot{w}}}{i_B}\left(\frac{\dot{w}}{V}\right) - \frac{m_q}{i_B}\left[\hat{t}\left(\frac{\dot{w}}{V}\right) - z_w\left(\frac{w}{V}\right)\right] + \dot{q}\hat{t}^2 = 0$$

i.e. $$\frac{z_w m_q - \mu_1 m_w}{i_B}\left(\frac{w}{V}\right) - \frac{m_q + m_{\dot{w}}}{i_B}\hat{t}\left(\frac{\dot{w}}{V}\right) + \hat{t}^2\dot{q} = 0.$$

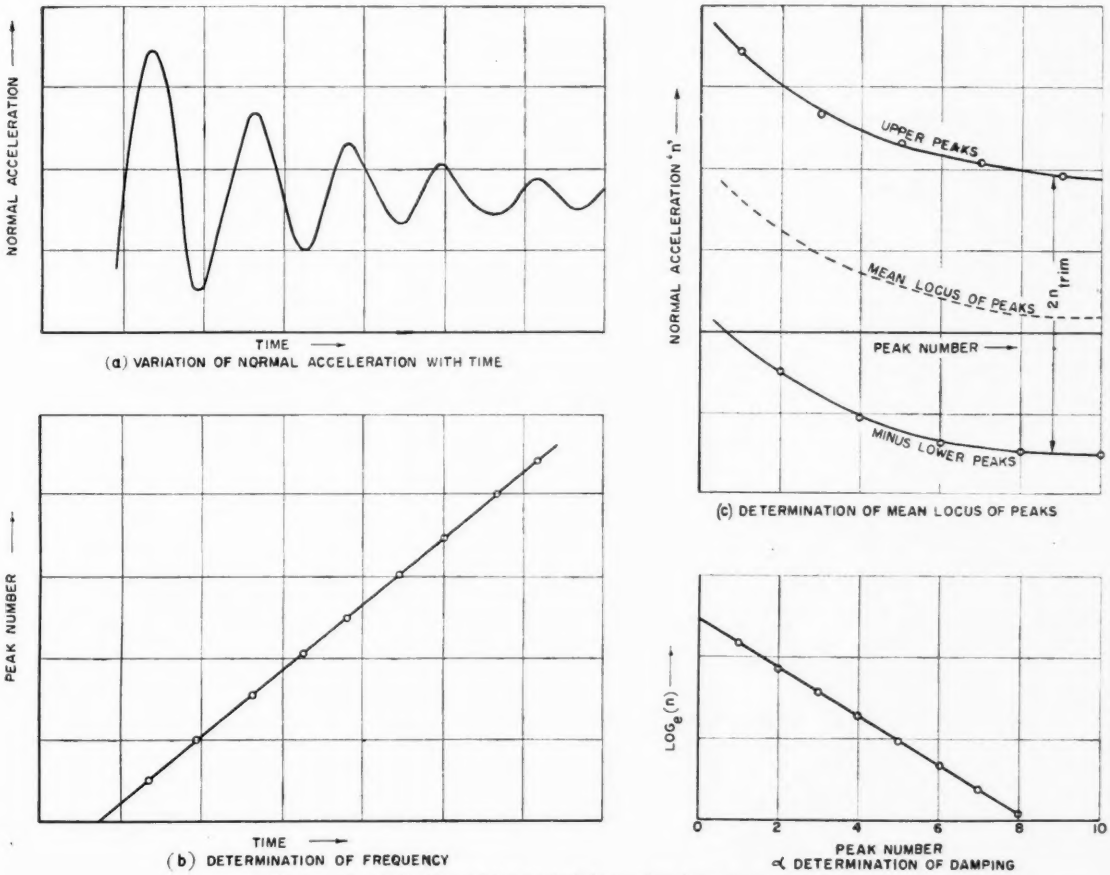

FIGURE 45. Derivation of the basic information from one response.

Now $z_w m_q \ll \mu_1 m_w$

and if the velocity is assumed constant in the interval being considered

$$\frac{w}{V} = \alpha \quad \text{and} \quad \frac{\dot{w}}{V} = \dot{\alpha}$$

hence

$$m_w = \frac{\hat{t}}{\mu_1} \frac{[i_B \hat{t} \dot{q} - (m_q + m_{\dot{w}})(\dot{\alpha})]}{\alpha}$$

and $$m_w = \frac{\partial C_m}{\partial \alpha}.$$

Therefore $$C_m = \frac{i_B \hat{t}^2}{\mu_1} \dot{q} - \frac{\hat{t}}{\mu_1} (m_q + m_{\dot{w}}) \dot{\alpha} + C_{m_0}.$$

- $\dot{q}$ may be measured by an angular accelerometer or by displaced normal accelerometers.
- $\dot{\alpha}$ may be derived from the incidence vane measurements of α against time.

Control Effectiveness

Control effectiveness is given in the form $\left(\frac{\Delta C_L}{\Delta \eta}\right)_{\text{trim}}$.

C_L is obtained from the plot of g against peak number (Fig. 45) and $\Delta\eta$ is the preset value of control deflection.

The Focal Point Method of Determining Lift-Curve Slope

In the early days of dynamic stability tests in free flight, a suitable incidence vane was not available and a method was devised for determining lift-curve slope from the readings of two or more normal accelerometers displaced along the X-axis of the model. This method is still applied to check the $\partial C_L/\partial \alpha$ values derived from incidence vane and normal accelerometer. It has one advantage over the use of an incidence vane in that it avoids having a non-representative nose on the model.

Suppose the test vehicle is equipped with two normal accelerometers; one at the c.g. and one in the nose, say, at a distance d from the c.g. Then if the peak values from the two at any instant are n and n_d we may write

$$n = \frac{1}{\omega_n^2} [a_1 \pm a_2 e^{-\lambda (t_p - t_0)} \sin \delta] \quad . \quad . \quad (7)$$

$$n_d = \frac{1}{\omega_n^2} [b_1 \pm b_2 e^{-\lambda (t_{pd} - t_0)} \sin \delta] \quad . \quad (8)$$

where

ω_n undamped natural frequency
t_p, t_{pd} times to peak
t_0 arbitrary time of origin.
a_1, a_2, b_1, b_2 are constants
$a_1 = b_1$ = steady state acceleration.

Now

$$\dot{q}(t) = [n(t) - n_d(t)] \frac{g}{d} \quad . \quad . \quad . \quad (9)$$

and if we assume that $t_d = t_{dp}$ to a close approximation equation (9) may be written

$$\dot{q} t_p = \frac{g}{d\omega_n^2} [a_2 - b_2] \sin \delta e^{-\lambda (t_p - t_0)}. \quad . \quad (10)$$

At the peaks of the oscillation

$$\dot{w} = 0 = \dot{\alpha} V$$

and the equations of motion in derivative form (4) and (5) reduce to

$$-\frac{z_w}{V} w = \hat{t} q$$

$$-\frac{\mu_1 m_w}{V i_B} - \frac{\hat{t} m_q}{i_B} q + \hat{t}^2 \dot{q} = 0.$$

Solving these two equations gives

$$\frac{1}{i_B} [z_w m_q - \mu_1 m_w] = \frac{-\dot{q} \hat{t}^2}{\left(\frac{w}{V}\right)_{\max}}$$

and since from equation (6)

$$\frac{1}{i_B} [z_w m_q - \mu_1 m_w] = \omega_n^2 \hat{t}^2$$

we may write

$$|\Delta \alpha|_{\max} = \left(\frac{w}{V}\right)_{\max} = \frac{|\dot{q}|}{\omega_n^2}$$

i.e. from equation (10)

$$\Delta \alpha_{\max} = \frac{g}{d\omega_n^4} (a_2 - b_2) \sin \delta e^{-\lambda (t_p - t_0)}$$

$$\frac{\Delta n_{\max}}{\Delta \alpha_{\max}} = \frac{\frac{a_2}{\omega_n^2} e^{-\lambda (t_p - t_0)} \sin \delta}{\frac{g}{d\omega_n^4} (a_2 - b_2) e^{-\lambda (t_p - t_0)} \sin \delta}$$

hence $$= \frac{a_2 \omega_n^2}{g (a_2 - b_2)} d.$$

$$z_w = -\frac{\hat{t} \omega_n^2}{V} \frac{a_2}{a_2 - b_2} d. \quad . \quad (11)$$

The geometrical interpretation of this expression is illustrated in Fig. 46.

If the peak normal accelerations are plotted as a function of axial distance and corresponding peaks joined, the rays will intersect at a common point on the axis (the "focal point") and the distance between focal point and c.g. is then a function of z_w.

$$D = -z_w \frac{V}{\omega_n^2 \hat{t}}$$

hence $$z_w = -\frac{\omega_n^2 \hat{t}}{V} D. \quad . \quad . \quad (12)$$

Further, since

$$\omega_n^2 \hat{t}^2 = \frac{1}{i_B} (z_w m_q - \mu_1 m_w)$$

$$\approx -\frac{\mu_1 m_w}{i_B}$$

by substitution in (12)

$$z_w = \frac{\mu_1 m_w}{i_B \hat{t} V} D$$

i.e. $$-\frac{\partial C_m}{\partial C_L} = \frac{m_w}{z_w} = \frac{i_B \bar{c}}{D}$$

i.e. lift-curve slope and manoeuvre margin can be determined from the focal distance.

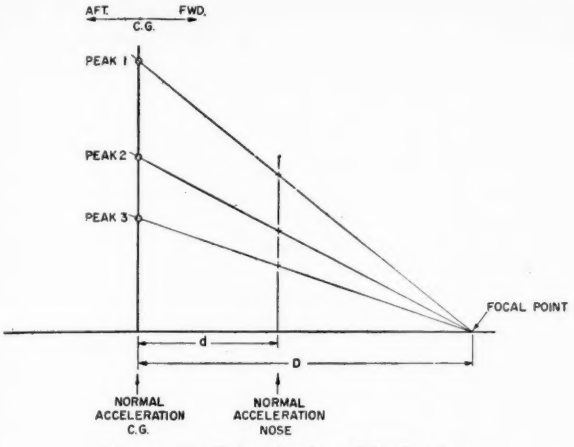

FIGURE 46. Determination of focal point.

APPENDIX III

A NOTE ON ACCURACY

The overall accuracy of any technique for investigating aerodynamic phenomena falls broadly into two parts: accuracy of representation, and accuracy of measurement. Reynolds number is the ruling parameter of accurate representation, although the effects of model distortion to accommodate supports or instruments may also enter. In free-flight testing the accuracy of representation is high: the Reynolds numbers approach those appropriate to full-scale aircraft at altitude, distortion of the model is rarely necessary and there are no restraints either from walls or supports to contribute their penalty of uncertainty. The major inaccuracies in the technique arise from the transducers and their associated telemetry.

If the overall accuracy of measurement were simply the sums of the individual component inaccuracies then a statement of overall accuracy would be relatively easy. Unfortunately, it is rare for an instrument installation to be so tailored to the model behaviour that it operates under optimum conditions throughout the flight. Amplitude and frequencies vary with the model velocity, the drag at subsonic speeds may be but a fifth or a quarter of the supersonic value, and so on. The values of accuracy quoted here are, therefore, based on the known values of transducer and telemetry accuracy leavened by the experience gained from flights on models of widely differing characteristics.

Velocity and Mach Number

Doppler with trajectory corrections included gives apparent flight-path velocity to ± 2 ft./sec. Under favourable conditions the wind velocity uncertainty is probably about ± 2 ft./sec. and the uncertainty in ambient temperature $\pm 1°$C., giving an uncertainty in Mach number of about $\pm 0{\cdot}6$ per cent. at $M = 1{\cdot}0$.

Under gusty conditions the error in wind-speed determination may well be greater than that quoted and to avoid this and also to avoid undue disturbance of the model by atmospheric turbulence most free-flight trials are confined to days when the wind speed is less than 20 knots at the operating altitude.

Drag at Zero Lift

For a test vehicle tracked by Doppler and equipped with a single-channel telemetry unit measuring longitudinal acceleration, the uncertainty in drag coefficient is about ± 4 per cent. at supersonic speeds and ± 12-15 per cent. at subsonic speeds.

Roll Tests

Rates of roll in the range 3,000-1,500 deg./sec. are usual in fixed-control roll test vehicles and the radio spinsonde will measure these with an uncertainty of ± 30 deg./sec.: allowing for errors in velocity and control setting, l_ξ/I_p may be determined to within ± 5 per cent.

Longitudinal Stability

The uncertainty in lift coefficient is about ± 4 per cent. and that in incidence ± 3 per cent. giving an uncertainty in $\partial C_L/\partial\alpha$ of ± 7 per cent.: the accuracy of frequency measurement is high and ω may be determined to within ± 2 per cent., giving an uncertainty of ± 9 per cent. in $\partial C_m/\partial C_L$. For the focal point method the uncertainty in $\partial C_m/\partial\alpha$ is ± 6 per cent. and in $\partial C_L/\partial\alpha$ ± 8 per cent., for an installation which allows the full ranges of the various instruments to be used: this state of affairs is not always possible and the uncertainties may then increase.

For the rotary damping quantity $(m_q + m_{\dot{w}})$, the accuracy of determination is greatly dependent upon the inertial and aerodynamic characteristics of each individual model design. Since

$$(m_q + m_{\dot{w}}) = i_B\,(2\lambda\hat{l} - z_w)$$

and both λ and z_w may be subject to errors of the order of ± 6 per cent., large percentage errors in $(m_q + m_{\dot{w}})$ are possible. A low value of i_B is desirable in the determination of rotary damping but such are the restrictions on model design imposed by other desiderata that the value of moment of inertia is virtually beyond the control of the designer. In general, the inaccuracy in evaluation of the rotary damping is not serious where tests on specific designs are being made, since the total damping

$$-\left(z_w + \frac{m_q + m_{\dot{w}}}{i_B}\right)$$

is the important parameter and the rotary component only enters as a correction for the differing values of i_B between model and full scale.

DISCUSSION

MR. N. E. ROWE: The Lecture had been a most stimulating one from many points of view. One was impressed by the great ingenuity of the work, especially the instrumentation side of it and the great amount of data which could be obtained by this kind of test. He would like to congratulate and compliment the authors of the paper on its presentation. Neither of them spoke from the written word and they gave a very fresh presentation of the whole thing.

MR. HANDEL DAVIES (Scientific Adviser to the Air Ministry, *Fellow*): It was a real pleasure and a

privilege for him to open the discussion for two reasons. One was that this was the first Main Lecture at a Branch which had a very special place in his own heart, since he had played some part in its formation; secondly, because of the excellence of the Lecture. He would like to congratulate the lecturers and also their colleagues at the R.A.E. for the fine work which lay behind the Lecture. He thought that they had been too modest in describing their activities and he would like to try to correct this by drawing attention to the extreme difficulty and complexity of the technique. It was worth remembering for example, that all the measurements had to be made in a period of less than twelve seconds, which was the normal time of flight of the models used in the free flight technique; and that manoeuvres of the model often involved longitudinal oscillations of 12 or 16 a second and rates of roll of about 3,000 degrees a second; and at the end of the whole test the model was destroyed! Indeed he thought the only advantage which those responsible for free flight tests had over them at Boscombe was that they did not have to get the pilot's agreement to what went on. He would like to emphasise too that they had brought this technique to the success which they had illustrated in the lecture with the aid of an incredibly small team, far smaller than the teams engaged in similar work in the United States.

Mr. Hufton generously mentioned the names of two people who were involved in the early stages of this work. There was one other man whose name he would like to see recorded in association with the work, since he was responsible for making the decision in 1947 to go ahead with the free flight technique in this country. He referred to the late Mr. W. G. A. Perring, then the Director of the R.A.E.

There was one aspect which had always worried him in this field and that was the application of the technique to longitudinal stability measurements. Mr. Hamilton drew attention to this. It was a very weak part of the whole thing he thought, because the theoretical background on which the application of the technique to stability measurement was based had at least two major weaknesses. One was that the tests had to be done with a very much larger manoeuvre margin than was the case on the full-scale aircraft, in order to achieve a sufficient number of oscillations in a given time and over a given Mach number range. That was unfortunate particularly in the transonic region where it was impossible to make an adequate correction for it. The other weakness was the fact that the application of the method depended on the assumption of the so-called quasi-steady theory. Unfortunately, the variations in damping which took place in the transonic speed range were themselves associated with the breakdown in the quasi-steady theory in this region. In the early days of the technique he had been very sceptical indeed about the chances of success in this field. Nevertheless the one example reported by the Lecturers of a comparison between the results obtained by the technique and full-scale flight (Fig. 38 in the paper) did show remarkably good agreement. Were there any other examples which showed such good agreement in this field?

His own conviction was that this technique was one which had quite a number of years of use left in it yet. He thought it was the only technique in which something approaching the full-scale conditions could be achieved and he would like to look on it as a sort of "half-way house" between the theoretical and wind-tunnel testing on the one hand and the full-scale testing.

R. P. DICKINSON (Superintendent of Performance, A. & A.E.E., *Associate Fellow*): He did not think they could let this opportunity slip of going back 10 years to the time when the country was faced with the decision of flying full-scale supersonically, or doing the sort of work the Lecturers had described. For the past 10 years he had been involved in that argument more times than he liked to mention. The official reason given was that they could build a strong aeroplane and go transonic and that would be perfectly straightforward, but it would not help very much in designing operational supersonic aeroplanes. He thought this was the day of reckoning, for they had seen that night that they could get the basic information by this technique as opposed to building a freak aeroplane for the job. Even so, the special aircraft which had been built had "blazed the trail".

He had not previously been convinced that there was any place now for free flight technique, but he had been convinced, now, to some extent, by the lecture that there were jobs left for them to do. Nevertheless he had been equally impressed by tunnel people. He had had a demonstration of an intermittent tunnel recently which somebody had put up in six months for £3,000 and it did a Mach Number of 1.5 and gave 15 to 20 seconds running every quarter of an hour. He thought that a big claim could be made for that alternative approach. Nevertheless he was convinced now that there was some work ahead for this technique. He was relieved to see that there was a possibility of getting early data on kinetic heating, and hoped that that would be taken seriously. He did not see any other quick method of getting such results; on dynamic testing, one of their main problems as everybody knew now, was the yaw divergence phenomenon which seemed to him just the thing for full flight technique. The only alternative seemed to be simulator work which, though extremely valuable, was perhaps not fully convincing and needed some follow-up trial such as this.

On page 164 on the longitudinal stability problem, it was said that static stability measurement could not be obtained in accelerated flight. In full-scale work this was now being done to some extent, although it was not thought possible before; quite good agreement was being obtained with steady condition measurements. Would Mr. Hufton advise on what was the limiting longitudinal acceleration for this to be a feasible technique? On short period work he was glad to say that full-scale emphasis was on that aspect of longitudinal stability; however, on the damping of the short period, they had not yet reached the stage where they were analysing the result of the short period oscillation to obtain aerodynamic quantities from it. He thought they might be driven to that.

He thought they were gradually catching up with the same sort of troubles that Mr. Hufton and Mr. Hamilton had had; with the short endurance rocket aircraft they might have to do this transient short period oscillation analysis to get the aerodynamic parameters, rather than doing stability somewhat longhand as now.

In that connection he was surprised to see that Neumark's name did not appear in the references. He thought that he had produced data some time ago on the way of analysing these short period oscillations. Obviously, as the previous speaker had said, there was a tremendous achievement in the instrument field. He could not understand why the full-scale people could not take more advantage of this work; it was most admirable. Telemetering was seen in its ideal application, although he did not think it was wanted for the full-scale work, except in the early stages of prototype flying. They had already made tremendous use of the records obtained by free flight technique and had leaned on those records very heavily in planning full-scale flight tests and knowing just the things to look for. He thought he might be right in saying that the Lecturers left out one classic from their work. Did they not in this work demonstrate aileron reversal with compressibilty at one stage?

D. A. WOODLEY (Asst. Chief Designer, Sir W. G. Armstrong Whitworth Aircraft Ltd., *Associate Fellow*): He did not feel so unhappy as Mr. Dickinson appeared to be about this technique but he would like to thank him for the unsolicited advertisement for their intermittent tunnel.

As a compendium of knowledge and solid experience he thought the paper must be of classic importance. There were a few other problems in the aircraft field where he thought the free flight technique could be of use. There was the constant problem of losing things from aircraft and he thought there that models could help in capsule parting, cockpit hood jettisoning—he was not trying to put the blower tunnel out of work—and bomb release. There were other problems such as rain erosion and cockpit vision. He knew they all involved different types of models, they wanted boost sustaining, and there were new difficulties of recovery and of recording. It might be that the latter problems belonged more correctly to the rocket sled but it was unfortunate that the only one which seemed to be working at the present time was not in a zone of English weather.

W. G. MOLYNEUX (Royal Aircraft Establishment): The lecture had been a somewhat revealing one. As a co-user of the Larkhill range it had been his unfortunate lot on many occasions to have his own models held up while one of these models was prepared for test. Having heard something of the complicated mechanisms that these rounds contained he could now well understand the delay.

His own particular activity was concerned with flutter testing and oscillatory aerodynamic derivative measurements by the free-flight technique and in consequence he found that part of the lecture on oscillatory stability derivative measurements of particular interest. Reading through the paper however, it seemed that less derivatives were required to describe the stability oscillation in pitch and vertical translation than would be considered necessary for flutter. For stability four derivatives seemed to be adequate, whereas for flutter they required a minimum of six, if they ignored the derivatives due to displacement and virtual inertia. Would Mr. Hamilton clarify this point?

Two methods of exciting the short-period oscillation were described, namely rocket charges and programmed elevator, both of which produced an external force on the model; had the possibility of internal excitation been considered? One possibility was a heavy, spring-constrained slug inside the body of the model, free to pitch relative to the model against the springs. By oscillating the slug one got an opposing oscillation of the model and by varying the spring constraint he believed that the frequency of the stability oscillation could be controlled; which might be an advantage if a representative frequency parameter were required. It might in fact be less complicated than the programmed elevator, although elevator effectiveness could not be measured.

The speakers had put forward some fairly cogent arguments in favour of retaining the free-flight model technique for aerodynamic research and his own experience with flutter models lent these arguments further weight. Flutter effects were dangerous to investigate in wind tunnels, largely because of danger of damage to the tunnel that would result with the possibility of a flutter model disintegrating. However, the arguments used did not mention the relative cost of wind tunnel and free-flight models and it seemed to him that the free-flight models of the type described might well be far more expensive than the comparable wind tunnel model. Perhaps the speakers would comment on those points.

A. C. S. PINDAR (Royal Aircraft Establishment, *Associate Fellow*): Speaking from the point of view of one concerned with wind tunnel testing in the transonic range he supported Mr. Hufton's contention that the free flight work should be continued as something complementary to wind tunnel testing. Although transonic tunnels were now operating they had many problems, both as regards the distortions to the models, as mentioned in the paper, and also on the matter of the interference which was caused by the means of support. He hoped that the change of emphasis in free-flight work towards higher supersonic speeds would not mean that they would not continue to get free-flight experiments down through the transonic range into the high subsonic speed range, because it seemed to him that it was possible that the free-flight people could help a great deal in coping with the difficult problems of interference in the transonic tunnel. A simple example was the fact that, especially at transonic speeds, it was difficult to know just what could be tolerated in the way of a support sting on account of its interference effect on the base pressure on the model; he

thought there had been experiments to investigate this sting interference effect.

He was interested to hear of the possible extension of the free-flight techniques to include higher incidences. He had not studied these longitudinal stability investigations very much on the free-flight side but he wondered if it would be possible for the free-flight investigations to contend with the sort of pitching instability effects which had been predominant in recent years and which showed in the wind tunnels as very marked, abrupt changes, kinks in the curves of pitching moment against lift coefficient.

On the question of the time taken to get models made and the relative time it took for free-flight experiments on the one hand and wind tunnel experiments on the other, what was the comparison between the accuracy to which the models were made? He meant the accuracy of contour. Strength and rigidity played a large part in the long time that it took to make wind tunnel models; was the accuracy which was allowed finer or more tolerant than was called for in the making of wind tunnel models?

In discussing aeroelastic distortion of the free-flight models it was mentioned that there was considerable distortion in the earlier models for control tests, but this point was not mentioned in discussing the longitudinal tests with models which were programmed by means of rockets or elevators and which suffered transverse accelerations. In these longitudinal tests was there distortion of the wings of the models and if so did they have any marked effect on probable validity of the final results?

W. J. G. PINSKER (Royal Aircraft Establishment): In view of the scepticism of previous speakers he would like to defend the simulator and attempt to define its proper terms of reference, as well as its real limitations.

The chief virtues of the (electronic or electromechanical) simulator were extremely low running costs, flexibility and speed of computation, requiring no expendable models.

The study of aircraft dynamics, such as the problem of inertia cross-coupling in rolling manoeuvres, resolved largely into the computation of straightforward dynamics and kinematic aircraft motions and had to cover essentially the full flight regime and should also show the effects of modifications to the basic aircraft configuration. Even a minute fraction of such a programme could not conceivably be realised in free-flight tests—not even in a free-flight tunnel, where at least the model survived the individual test. An electronic simulator, on the other hand, would do this virtually in a matter of days; consuming perhaps 5 kW of power and the labour of two members of the staff.

Of course, the simulator must represent correctly all the relevant features of the problem, but this applied equally to the free-flight model, where one might "forget" to represent such features as say, control freedom, structural flexibility or minor geometric details if their effects on a given problem were not initially anticipated in the planning of the experiment.

Any aerodynamic type of test, such as wind tunnel measurements or free-flight models, or similarly the free-flight tunnel, should be reserved for and, as far as he could see, had only been successful in tackling problems of predominantly aerodynamic character and its application should be generally confined to this field.

MR. ROWE: They had heard a very fine lecture. Someone had described it as a classic. He was quite sure that it would be consulted very often in the annals of the Society because it had given extremely valuable information, had talked about a technique and had given results which were in the category of things they wanted to know.

Mr. Handel Davies had said that this was the first Main Society Lecture at Boscombe Down. It was a long way along in the series now of Main Society Lectures which had started about five years ago with two at the Branches and had now grown to four annually. The whole idea had proved a great success and he was sure that it had been greatly appreciated that evening because they had been able to hear a discourse and a discussion which otherwise they could only hear in London, so that the idea of taking the Main Society Lectures to the Branches was again adequately justified.

He was very glad to see Mr. Handel Davies, not only because he was an old friend but because he was now the Chairman of the Branches Committee and hence responsible to the Council for the general growth and well being of the Branches and he was sure he would do that with tremendous success. As they knew he had personally been interested in the Branches for many years, and in the Council and in the Society generally, they looked to the Branches for a great deal of their general health. The Branches could do things which the Main Society could not do. The general spread of aeronautical knowledge, and accounts of the science and engineering of aeronautics was brought out to the whole country in a way that would not be possible at all if they had London occasions only. There were 22 Branches and they stretched from Belfast in the West over to Brough in the East (that was the Branch where he belonged himself) and recently he was at Merthyr Tydfil, down in the 'wilds' of Wales—he hoped he was not offending the Chairman of the Branches Committee in so referring to his native land—but there they had a most healthy branch and it was extremely enjoyable to be there.

They relied on the Branches also for recruitment. They formed a base from which young men could move forward. They could learn to discuss on their home 'pitch.' They could hear very good lectures and they could come forward in the Society. The Council were making a big drive in the Society for increased membership. They thought that the Society should move forward. They thought the work they did compared well with any engineering or scientific work that was done, and that out of the challenge of aeronautics had come a body of engineers and scientists of the highest professional attainments. It seemed clear therefore that the Society should move forward from its present membership, which was about 7,500 in Great Britain and

1,000 in other parts of the Commonwealth and the world generally—a total of 8,500. The Future Policy Committee of the Society had looked at this position very carefully and concluded the membership could readily be doubled judged against the strength of the aeronautical activity in this country and they were inviting firms and others concerned to take this seriously and to recruit as far as they could to increase the strength.

As they knew, the Society was now a Chartered body. In other words this Society was now the recognised professional body for aeronautical scientists and engineers in this country. It had been charged by being given a Charter, a Royal Charter, to become the Corporate body representing aeronautics and in that sense he thought that all of them, especially their young students and graduates, should join with the Society so that they became associated at an early stage with the body which could help their best interests. He hoped that the Society would move forward by means of recruiting from this Branch, as it is doing already by recruiting from other Branches.

The Branches were of course autonomous. They were not formed entirely by members of the Society and in that they differed from other professional bodies, who had their branches but all the members of the Branches must necessarily be members of the parent body. He thought that their own Society must continue in the dual rôle with adequate professional gradings for its members, but not excluding those who were interested in this fascinating business of aviation and aeronautics but who had no professional qualification. In their gradings as they knew, they had the membership of Companion which looked after what one might call the amateur element, an extremely valuable one in a business such as theirs, which was moving at such a rate. In their Branches they had the same facilities to include those interested in aviation but who were not professionally qualified to join the main Society. So that the Branches discharged this very valuable function, of allowing those who were interested but not professionally qualified to come into their discussions and hear the latest things in aeronautics by those best qualified to tell them.

He had found in the Branches, as in so many other things, that where the work was done on a voluntary basis it rested on the shoulders of comparatively few people and he would like to thank the committee at Boscombe Down for making this such a very good occasion; and particularly the Branch Secretary, Mr. Higton, who was a great enthusiast for Branch affairs; they had had a first rate meeting. Finally he would like to thank their President for the use of the hall.

A. B. HAINES (Chief Aerodynamicist, Aircraft Research Association Ltd. *Associate Fellow*) *contributed*: He had been connected for several years with the work of high subsonic speed or transonic tunnels and was most interested in the remarks of the Lecturers concerning the relative usefulness of the wind tunnel and free-flight techniques. He would completely agree with their general outlook that the development of transonic tunnels certainly did not eliminate the need for extensive use of the free-flight technique. The two techniques should in fact be regarded as being, in general, complementary rather than alternative. In many cases, a series of relatively cheap free-flight tests might often point the way to where a full and detailed wind tunnel investigation should be started. In short, the free-flight tests might often serve to indicate what should be tested in the wind tunnel, whereas the wind tunnel might often serve to expand the results obtained in free flight. Further, he would agree that there were certain forms of tests such as dynamic stability experiments that could be made more simply and perhaps more reliably in free flight.

Free flight tests also had the benefit of reproducing much more closely than in most wind tunnels, the Reynolds numbers appropriate to the full-scale aircraft. The fact that the test Reynolds numbers were high did not, however, mean that no attention need be paid to the state of the boundary layer. It was likely that at zero incidence transition would occur fairly far back on the smooth wings of the models, particularly if they had only a small amount of sweepback. On the full-scale aircraft, however, a farther forward position for transition was more probable and this difference might result in the boundary layer ahead of the shock wave being laminar on the model and turbulent on the aircraft. It was important to realise that at the relatively high Reynolds numbers of free-flight testing, the effects of shock-induced separations on the model with the laminar layer ahead of the shock might be *less* and not more pronounced than on the full-scale aircraft. The results for the model might, therefore, present an over-optimistic rather than a conservative picture.

The reason for this could be explained briefly as follows:—

A laminar boundary layer admittedly separated under the influence of a smaller adverse pressure gradient than that needed to separate a turbulent layer, but the tendency for subsequent re-attachment was also much greater with the laminar layer. With the latter, separation might occur well upstream of the main shock wave, thus resulting in a weak forward limb to the shock and hence, in most of the pressure rise being concentrated in the rear limb. When this rear strong shock met the thick separated boundary layer, it was reflected as an expansion which served to deflect the separated layer towards the surface and in many cases to cause re-attachment as a turbulent layer. Subsonic flow was then usually restored through a final near-normal shock which was frequently not strong enough to cause a separation of the re-attached turbulent layer. On the other hand, if the boundary layer ahead of the shock system were turbulent and if the shock were strong enough to cause separation, most of the pressure rise would usually be in the forward limb of the shock, the rear limb was then only rarely reflected as an expansion and re-attachment, although not impossible (in fact, it had been noted on various aircraft in flight), was less likely. Hence, there was a greater risk of a separation with no re-attachment ahead of the trailing edge. This contrast between the behaviour of laminar and turbulent

boundary layers at high Reynolds numbers was first pointed out by Dr. Holder and Mr. Pearcey of the N.P.L.

Since, therefore, the results obtained at high Reynolds numbers with a laminar boundary layer ahead of the shock might often not be conservative, they should be interpreted with care. It was certainly important to know where transition occurred. This might be particularly so for wings with swept trailing edges for which the shock wave and an associated separation might remain ahead of the trailing edge over a significant range of Mach numbers beyond 1.0: at incidence, with a wing of appropriate plan form, such characteristics had been observed even at Mach numbers as high as 1.8. On the other hand, it was possible that with the swept wings, transition even on the free flight models, occurred close to the leading edge. Had the lecturers any evidence on this point?

Another aspect of the question of whether transition occurred and the state of the boundary layer in general, was that if they were not the same on all models of a comparative series, then the comparison between the measured drag results for different models, *e.g.* the "area rule" comparisons contained in the paper might not be accurate quantitatively (although this clearly did not affect the striking reduction in drag near $M=1$ achieved in the particular area rule application illustrated in Fig. 27).

He would like to support the case for improving the accuracy of measurements of drag due to lift which, as pointed out in the paper, was at present somewhat limited, particularly for cases where little leading edge suction was realised. While the great bulk of data on this characteristic was always likely to be provided by the wind tunnel, some checks for wings of various representative plan forms and section shapes at the higher Reynolds numbers possible in free flight would always be desirable. Reduction of this lift-dependent drag by use of appropriate camber and twist might well be an important field of future research.

Despite improvements, it would appear that there was still a tendency for the free-flight technique to smooth out sudden changes in the characteristics that might occur near $M=1$. This tendency might be less of a drawback in the future than in the past in view of the introduction of ever thinner wings and wing-body combinations of improved area distributions. However, would the lecturers feel this still to be a matter of concern? The kinks actually occurring in some of the measured results were likewise a warning to the planner of wind tunnel tests not to restrict his data to a few discrete Mach numbers but to keep the intervals between test Mach numbers near $M=1.0$ reasonably small.

R. A. J. WHITE (*Associate Fellow*) *contributed*: An explanation given for the cause of sonic bangs was that the " bang " was created when the velocity component of the vehicle towards the observer was sonic. This would account for the triple bang which occurred with a separating test vehicle but how did this theory account for the triple bang sometimes heard from conventional aircraft?

Could the authors give some indication of the more elegant methods now under development for heat transfer measurement and also, means for detecting the state of the boundary layer?

It was inevitable with the use of telemetering equipment that numbers of continuous records were obtained which had to be analysed. Was automatic computing equipment being used to speed up the analysis of results and if so, what type?

MR. HUFTON

MR. DICKINSON: Mr. Dickinson queried how the impact of intermittent tunnels would be reflected in their work; he (Mr. Hufton) had also got several intermittent tunnels to look after, so he could really compare them. It was perfectly true that an intermittent tunnel going up to Mach numbers of say, about 4.5, with Reynolds numbers of the same order as continuous tunnels, could be made very readily. He doubted whether they could be stretched to the free-flight Reynolds number. Roughly speaking he thought they would be of about 16 ft. diameter with stagnation pressures of about 5, and even with a considerable storage capacity, something like 100,000 horse power would be needed to top-up for runs of about a sixtieth of the topping-up time.

Even with such intermittent tunnels he did not think they could reach the free-flight Reynolds number. The second thing was that they were still in difficulties about the model support. So that while he tended to agree that the intermittent tunnel was really a competitor of the continuous tunnel for a large amount of work, he did not think it really could cover the free-flight field.

He had some comments on measurement of longitudinal stability under accelerated conditions. There were really two problems there, as Mr. Handel Davies pointed out. There was the question of how one analysed the motion to obtain derivatives and then whether the derivatives under the accelerated conditions were the same as under practically steady conditions. He thought that as far as the measurement technique, and analysis were concerned they were all right.

The statement on page 164 to which Mr. Dickinson referred was not meant to imply that static stability measurements could not be obtained during accelerated full-scale flights. It referred to the high decelerations and very short time of flight occurring in free-flight trials. There were other factors such as range safety and model design which would eliminate the 'long hand' method of static stability assessment from free-flight testing.

With some of the rocket-powered aircraft the time of flight would be so short that it would be extremely desirable to try to get measurements under accelerated conditions and while those accelerations would not be so severe as in the free-flight case, he thought the general techniques that had been developed for analysing the free-flight motions were going to be valuable.

On the question of whether these derivatives would actually represent the derivatives that would exist under non-accelerated conditions, he thought that at low subsonic and at supersonic speeds they were fairly happy, but there was certainly some worry transonically.

Presumably the report of Dr. Neumark's that Mr. Dickinson referred to was his work on methods of analysing the short-period oscillations of full-scale aircraft to obtain dynamic stability derivatives.* Voepel's treatment of the short-period oscillation was aimed specifically at free-flight tests and had some advantages in application for this work, compared with Neumark's.

A number of speakers had made complimentary remarks about the instrumentation which had been developed for this work. A great deal of the credit for the development of these instruments went to the Instrumentation Department of the R.A.E., and the responsibility for telemetry rested with the Guided Weapons Department of the Establishment. A considerable contribution in this field was also due to a small group within the Free Flight section, which had modified and improved the production instruments to achieve the high standards necessary for aerodynamic investigation.

MR. PINDAR: Mr. Pindar was really agreeing on the complementary functions of tunnel and the free-flight technique with particular respect to the support troubles. These were quite serious. It was extraordinarily difficult nowadays—he did not know if aircraft designers realised how difficult they made things for tunnel people when they designed these long thin bodies with sharp ends—but it was very difficult to avoid making large modifications at the rear end of the fuselage, with doubtful effects upon the directional stability. Therein lay one of the advantages of the free-flight technique.

He wished they could put more effort into the high incidence effects; they would like to do more and thought it could be done; the weapon people did it; it was difficult and they would probably spend quite a lot of effort in doing it but he was fairly certain it would be well worth doing.

Their models were made to about 3 to 5/1,000 in. generally on contours. That, he thought for the size of model, was just about what should do for a wind tunnel model. One of the things that he had never really understood was why they got free-flight models apparently so much more quickly than wind tunnel models. It was the way things had been organised and it had just grown up like that. It seemed extraordinary that they could get one of these things full of all this complicated equipment in about six months while it took years to get a wind tunnel model. It did not seem to be just the accuracy with which they were made.

The large aeroelastic effects which were noted in the experiments on control effectiveness occurred in wings made of compressed wood. Apart from a few early technique development models, the free-flight work on stability had been done using wings of steel or light alloy. The maximum loads occurring on these models were generally low enough for aeroelastic effects to be negligible, although with thinner wings and higher incidence this state of affairs might no longer exist and some correction would be necessary. There were fairly well established theoretical methods for doing this.

MR. PINSKER: Mr. Pinsker raised the question of the use of the free-flight technique *vis-a-vis* the simulator. He thought a good many engineers would like to see some of the results from the simulator checked by real things that flew. There was a certain distrust of answers that were arrived at by millions of radio valves. They had had a considerable amount of trouble originally with some of their roll-damping models because, although they thought they had ample fin area on the boosters, the vehicles spiralled off on being fired, and broke up. That happened two or three times. Going back and looking at the conditions under which that occurred it was clear, looking at what the inertias were and the frequencies in the two planes, that those models were victims of the roll-coupled divergence. It might be a good thing to fire off hundreds of little models covering a range of different inertias with no instruments but just photographic records giving a "go" and "no go" plotted against the typical kind of carpet obtained by using the simulator.

MR. HAMILTON

MR. HANDEL DAVIES: He agreed that the unrepresentative c.g. position of free-flight models could lead to some difficulty in interpretation of the stability results. However, it was important to put this problem in its correct perspective. The derivatives determined from a typical free-flight longitudinal-stability investigation were z_w, m_w and $(m_q + m\dot{w})$. Of these, the first was independent of c.g. position, and the second could be converted into any c.g. position using only the information obtained from the test flight; it was therefore only the rotary damping terms which required recourse to information outside the experiment, *i.e.* to theory, for conversion to a new c.g. position. Obviously if the free-flight investigation were aimed at comparison with theoretical work, the c.g. position of the test was immaterial. When however, a model of a specific aircraft design was being flown a correction to the full-scale c.g. position could be made at subsonic and supersonic speeds using the well-established theory; the major difficulty arose in the region between $M = 0.8$ and $M = 1.2$ where the existing theories were not valid and viscous shock-wave effects might be predominant. It was not yet clear how important the non-representative c.g. position was in this region, but existing results had shown that the qualitative forecast of the full-scale behaviour which was provided by the uncorrected results was extremely valuable.

As had been noted in the paper, the unrepresentative c.g. position had one advantage, in that it produced a

*Analysis of Short-period Longitudinal Oscillations of an Aircraft. S. NEUMARK. R. & M. 2490.

value of the frequency parameter very close to the full-scale value, and thus, if the derivatives were functions of frequency, one would expect that the quasi-steady derivatives obtained from the free-flight tests would be applicable to the full-scale aircraft without further correction.

On the question of agreement between full-scale and free-flight model dynamic stability assessments, there were unfortunately very few quantitative full-scale results available in the transonic/supersonic regime. However, there was a considerable amount of qualitative flight evidence and this agreed in general with the quantitative results obtained from free-flight model tests on the appropriate aircraft.

MR. MOLYNEUX: The six stability derivatives to which Mr. Molyneux referred were presumably z_q, z_w, $z_{\dot{w}}$, and m_q, m_w, $m_{\dot{w}}$. Of these z_q and z_w were excluded from the mathematical treatment given in the Appendix to the paper. The reason for this was that these derivatives occurred in the equations of motion in the form z_q/μ and z_w/μ, μ was of the order of 100 for full-scale aircraft and of the order of 200 for free-flight models; the effect of these derivatives was therefore very small. (A fuller treatment of this point had been given by Neumark and Thorpe*).

The possibility of using internal excitation had been considered but there appeared to be little to choose in mechanical complication between this method and the programmed elevator. The internal excitation method had the disadvantage of not yielding any information on elevator effectiveness, which was one of the most important quantities to be obtained from free-flight trials.

Some comparisons between the cost of free-flight and wind tunnel models had been made but the two techniques produced their results in such differing forms that fair comparison on a basis of results per model was extremely difficult. The manufacturing time for a typical free-flight stability model was about 1,800 man-hours, and for a zero-lift model about 200 man-hours. For a tunnel model the manufacturing time was greatly dependent upon the degree of representation required and varied between 1,500 and 3,000 man-hours.

Some economy in the use of free-flight models could be achieved by recovering models which had been fired. This was achieved by breaking the model into several constituent parts during the flight by means of a carefully-positioned explosive charge. The separated components were moving with a relatively small velocity when they hit the ground and, using this technique, major components such as wings, had been recovered and re-used two or three times. The use of parachutes was also possible but presented problems in storage and operation.

MR. WOODLEY: A great deal of hard-won experience had been gained on the problem of releasing components from rocket motors travelling at high Mach number. The major problem in applying this technique to the investigation of the things Mr. Woodley mentioned, such as capsule parting and cockpit-hood jettisoning, was that of recording the behaviour and motion of the component. This could be done either by installing telemetry equipment within the released component or, by photographing it from the main test vehicle, but both these techniques presented obvious difficulties. Apart from the difficulty of producing the right atmospheric conditions to order, the investigation of such things as rain erosion was considerably hampered by the short time of test flight and he doubted whether representative results could be obtained.

MR. WHITE: There was no incompatibility between the theoretical conditions for the creation of a sonic bang and the triple bang which one sometimes heard from conventional aircraft. An aircraft which was accelerated from subsonic to low supersonic speed, and then decelerated to subsonic speed again in a dive, could produce theoretically any number of bangs at a given point on the ground, by making slight changes in flight path. The number of bangs that one heard was not always the theoretical maximum because of the inability of the ear to distinguish between noise pulses occurring very closely together, and because of the possible coalescence of shock waves from a relatively complicated shape like a full-scale aeroplane.

The more elegant methods mentioned in the paper referred only to the measurement of transition, although this and the measurement of heat transfer were obviously intimately connected. Briefly, the method proposed rested upon the great difference in heat-transfer rates which occurred between laminar and turbulent boundary layers. Under non-equilibrium conditions this was manifested by a marked difference between the skin temperature when the boundary layer was laminar, and that when it was turbulent. The problem then was to measure skin temperature, or more correctly differences in skin temperature, along the surface to be investigated. The associated instrumentation problems were formidable: the temperature measuring devices must not interfere with the surface flow nor must they affect the heat flow into the skin, and their response must be adequate to measure the very rapid changes in temperature associated with free-flight tests.

A start had been made on the automatic computation of records obtained from free-flight trials. The panoramic and histogram records (Figs. 11 and 12 of the paper) essentially required the conversion of a deflection into a number. This was done by using a film reader having a hand-operated lever to measure the deflection: the movement of the lever was converted into digital form by a strip commutator, and the output from the commutator was fed into an electric typewriter. The result was a tabulated series of values of the various parameters against time. This equipment would deal with linear calibrations only. For instruments having

*Theoretical Requirements of Tunnel Experiments for Determining Stability Derivatives in Oscillatory Longitudinal Disturbances. S. NEUMARK and A. W. THORPE. R. & M. 2903 (1950).

non-linear calibrations the digital output from the reader was fed into a card punch, and the cards were, in turn, fed into the DEUCE digital computor, which could be programmed to incorporate the non-linear calibrations. This particular development had been sponsored by the Free-Flight Group in consultation with the Mathematical Services Department of the R.A.E. A more ambitious scheme for mechanising the whole record by output from rocket-test-vehicle trials was being developed by the National Physical Laboratory.

MR. HAINES: They were grateful to Mr. Haines for his note on the behaviour of laminar and turbulent boundary layers at high Reynolds numbers and agreed that a knowledge of the position of transition was most important in all model testing. So far they had obtained only indirect evidence—deduced from subsonic profile drag measurements—to confirm their qualitative impression that the transition on free-flight models occurred very near the leading edge. In addition to the boundary layer work mentioned under the heading of heat transfer in the paper, they were making a series of simple-minded tests with transition strips to try and clarify some of the doubts on the state of the boundary layer in free flight.

For the specific case of drag models the normal procedure in comparing different models of a given series was to subtract the subsonic zero-lift drag, corrected for base pressure and form drag, from the measured supersonic drag. The resulting "drag increase" was used as a basis for comparison. This automatically allowed for differences in transition occurring at subsonic speeds but it implied that the change in skin friction effects from subsonic to supersonic speeds was of the same magnitude for all models.

They agreed with Mr. Haines that improvement in the accuracy of drag-due-to-lift measurements was one of the most important problems in free-flight testing. Unfortunately this measurement placed severe restrictions on the instrument designer and it was in the field of instrument design that the difficulty lay.

They were not clear whether in his last comment Mr. Haines was referring to instrument inaccuracies, or to a fundamental characteristic of the technique. They had no evidence to suggest that free-flight tests tended to smooth out sudden changes in aerodynamic characteristics near $M=1$. There was a statement in the paper on the tendencies of Doppler measurements of drag to smooth out sudden variations but this was entirely an instrument problem, which had been overcome by using accelerometer measurements of drag in the transonic region.

Air Crew Fatigue and Flight Time Limitation

by

Group Captain J. A. NEWTON, A.F.C., A.R.Ae.S.

(Chief, Flight Branch, International Civil Aviation Organization)

AT APPROXIMATELY 14.00 hours on an overcast December day in 1954, persons in the vicinity of Idlewild Airport, New York, were startled by a violent explosion followed by the signs of an intense fire. Investigation revealed that an incoming European aircraft, a DC-6B, had crashed into the pier supporting the approach lights to Runway 4, had been demolished by the impact and had carried 26 persons to their deaths in the icy waters of Jamaica Bay. An inquiry into the accident was made by the Civil Aeronautics Board and their findings published. The probable cause of the accident was determined as an erratic approach which resulted in a descent too low to avoid striking the pier, but a significant rider was added to the effect that a contributing factor was pilot fatigue due to the particular and difficult circumstances of the flight.

What is fatigue? What causes it, what are its results and what can be done to prevent its occurrence or to minimise its effects? Fatigue had been known in industry long before aviation became aware of its implications. It must have been a major problem in the early years of the Industrial Revolution, when workers were forced to carry out their duties under the worst possible conditions, for the least possible pay and the longest possible time; indeed, the first recorded recognition of fatigue in industry occurred in England with the passing of an Act of Parliament in 1802 by which the hours of work of children employed in the factories were limited and certain standards of ventilation and cleanliness were demanded of the factories that employed them. This Act has been followed through the years by numerous other labour acts put into force in many other countries and many other industries.

Industry has approached the solution of the problem in several ways. It was recognised that conditions of work and hours of duty had much to do with the onset of fatigue which manifested itself in a decrease in output, a lowering of efficiency and an increase in the number of accidents. A solution was not arrived at over-night; trade unions and other labour organisations have negotiated with management over a long period of time, but at present, hours of work in nearly every industry have been drastically reduced, practically to the optimum. Higher wages and other monetary benefits have removed much of the dissatisfaction of the worker and health and insurance plans do much to safeguard his future after retirement, or at such time as his useful working life may be at an end. To keep production at a height and costs at a reasonable level, industry has needed to co-ordinate such social improvement with vast technical strides so that a balance may be achieved and maintained between costs and profit.

But fatigue is still a relatively new concept in aviation. Studies are at present in progress on air crew fatigue in many states throughout the world in an endeavour to answer such questions of cause and effect —but these studies have succeeded largely in pointing up the complexities of the problem. Individual studies, however, have also been undertaken by many highly-trained technical specialists which have produced much interesting data.

It is reasonably simple to define physical fatigue resulting from over-exertion, but fatigue in the airman can hardly be considered to result solely from prolonged sustained activity. Many clinical studies have been undertaken in an effort to define fatigue in quantitative units but so many variables become obvious that this has proved impractical. Sir Frederick Bartlett, who has conducted many such studies, has developed a concept of skill fatigue in which he distinguishes between the fatigue produced by hard physical effort and that occasioned by work demanding little in continuous muscular reactions, but much in persistent concentration and a high degree of skill. He himself uses the term fatigue "to cover all those determinable changes in the expression of an activity which can be traced to the continuing exercise of that activity under its normal operational conditions, and which can be shown to lead, either immediately or after delay, to deterioration in the expression of that activity, or, more simply, to results within that activity that are not wanted".

Fatigue can, perhaps, be best described as a physiological state of tiredness, exhaustion or lassitude resulting from changes in body chemistry and physiology as a result of exertion which tends to inhibit further activity. Its onset is insidious and its victim may, or may not, be aware of its presence, which manifests itself in a steady deterioration of skill and efficiency and cannot be dissipated by stimuli. Air crew fatigue itself may then be divided into two stages, transient fatigue which is the normal fatigue manifest in a healthy individual following a period of exertion or excitement, and which responds to normal sleep, rest and freedom from such excitement, and cumulative fatigue which does not so respond but which may occur after transient fatigue when an individual has undergone stress of such great intensity that normal recuperation does not occur, and which may even result in a change in personality known as aeroneurosis.

In an attempt to discover the causes and results of fatigue in air crew, a series of experiments were

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conducted in England, usually referred to as the Cambridge Cockpit Studies, in which actual flying conditions were simulated as the tests were in progress. These experiments were governed by the idea that a pilot anticipates the dangers in flying and responds to such "anticipatory tension" (as it was named) with responses intended to remove the danger and so relax the tension. However, it was discovered that pronounced anticipatory tension can be the equivalent of anxiety. It was further thought that a pilot's skill is highly organised and, when disrupted, tends to produce errors and it is recognised that strong emotion, *e.g.* anxiety, leads in certain conditions to such a disorganisation of skill. After long periods at the controls in these tests a distinct deterioration in skill and accuracy became apparent and the subjects were willing to accept lower standards of accuracy and performance as they became more fatigued, failing to integrate the instruments as a whole while concentrating on one individually. The range of their attention diminished with a significant forgetfulness of peripheral instruments and landing-gear switches were frequently overlooked. There was a sudden increase in errors at the end of a simulated flight, indicating that a tired airman has a tendency to relax when in sight of his destination.

Numerous other studies of fatigue have been undertaken with the idea of providing preventive medicine, whereby a case of simple transient fatigue can be prevented from becoming cumulative fatigue and aeroneurosis. It is recognised that flying is a serious, responsible occupation requiring a high level of skill and intelligence. This high degree of intelligence often makes a pilot more conscious of his surroundings and minor discomforts. He is continually adding to his knowledge those things which he learns from each new flight and from the accidents he may witness or hear about. He may have acquired financial, social and family responsibilities and these, coupled with the responsibility he feels for his crew, his passengers and his aircraft, may begin to cause persistent, although unacknowledged, anxiety. Such feelings of anxiety and responsibility are entirely normal so long as the individual can handle his problems constructively, but when such anxiety is unresolved, tension increases. This continuing tension may keep him awake at night so that he feels stale and irritable, his digestion may be affected and he loses the desire to fly. Excessive work without frequent rest periods tends to affect the central nervous system, as well as bodily resistance and it has been found that cumulative and persistent anxiety, coupled with an inability to escape the responsibilities to which he is constantly subjected, may finally result in aeroneurosis which produces a definite change in the personality of the airman.

What causes fatigue in actual flight? Studies have produced many variables. The design of the aircraft itself, its size and weight, the location of instruments, the effort required to activate the controls, the noise and vibration to which the crew is subjected, together with variants of altitude, pressure, temperature, noxious gases and oxygen, all have an influence upon fatigue. Load—that is the number of items which have to be dealt with simultaneously or nearly simultaneously—is also a factor. Much depends too upon the duration of the flight, the frequency of landings and take-offs, the weather encountered and the amount of instrument flying undertaken, as prolonged mental strain, anxiety, or fear is known to result in a depleted reserve of energy.

Outside influences make themselves felt in the regions and climatic variations through which flights are made, the duration of stay in each climate, in poor aerodromes and inadequate ground services, in travel to and from the airfields, as well as such minor factors as meals at outlying stations. The amount of time spent in pre-flight duty, as well as delays in the planned flight with their resultant uncertainties and anxieties, are also significant contributors. Economic problems and personal worries relating to the pilot's home life are factors also in predisposing him to fatigue, since it is generally accepted that anxiety and emotional vexations may interfere with the judgment needed for accurately timed and co-ordinated movements and lead to preoccupation and absentmindedness. Pilots with nervous or neurotic temperaments aggravated by domestic troubles cannot conduct crew co-ordination or give the necessary confidence required when the crew faces unusual conditions. With all these variables and the possible different combinations thereof, States have found it impossible to provide regulations to cover all exigencies, but there is a substantial measure of uniformity in their ideas as to the ultimate limits of endurance of flight crews.

What are the results of fatigue in air crew? Air crew must be able to operate with maximum ability during certain peaks of activity, and it is significant that the Cambridge Studies already discussed showed that the effect of fatigue is greatest at the end of a flight when the demands for efficient performance are at their height. It is frequently necessary for the pilot to produce a reserve of energy and capacity at the end of a long flight in order to make an instrument approach, which, as in the case of the ill-fated aircraft previously mentioned, may be most difficult. The deterioration of skill and the acceptance of lowered standards noted in the Cambridge tests is particularly significant in relation to the over-looking of landing-gear switches, since mis-use of landing-gear is a common cause of accidents.

The findings of courts of inquiry into several recent and spectacularly disastrous accidents have included comments on the fatigue of the crews involved, underlining the fact that errors of judgment are more likely to occur when an airman is tired. It has been pointed out that first-class vision, with particular reference to convergence and accommodation, is a primary requirement for flying personnel, and that fatigue can noticeably impair such visual acuity. It is noteworthy that in several recent accidents where fatigue has been a contributing factor, visual errors (during landing and final approach) have been the primary errors leading to the accident.

From all the evidence gathered by States and in clinical experiments it would appear that fatigue is cumulative and leads to errors in judgment which can

endanger the safety of the aircraft, its passengers and its crew. The results of fatigue are, therefore, frequently deadly.

What can be done to prevent fatigue? Obviously a great deal depends upon the individual in the air crew. He must maintain good physical and mental health by following a programme of adequate exercise, too much is as harmful as too little, and good and adequate rest. He must abstain from excessive consumption of tobacco and alcohol and follow a healthful diet for, if he neglects to balance his diet, he may, for instance, eventually suffer a lack of Vitamin A which will affect his visual acuity. To compensate for such a reduction in vision during flight he will be constantly straining and the mental and bodily strain so caused will quickly tire him. He must do all he can to ensure that he approaches a flight in the best of health and well-rested. The operator for his part must do all in his power to assist his air crew by providing good, reliable aircraft, well-maintained and serviced, together with all possible ground aids.

Dr. Russell Davis of the United Kingdom in his comments on studies of pilot error, states that

> "It is reasonable to expect that if pilots come to regard flying as safe, from confidence in the conditions in which they fly, the accident rate will decline. On these grounds alone, everything possible should be done to relieve pilots of anxiety about the outcome of their flights. Traffic and other arrangements should be such that not only are the dangers reduced, but pilots should regard them as reduced. For the same reasons, careful briefing must be regarded as important".

Adequate health services and counsel wherever possible for emotional problems to relieve anxiety and tension, will assist the operator to keep his crews at the peak of their efficiency, and it must be remembered that the time and expense of producing a highly trained airman are lost when a crew member suffers fatigue. It is recognised that operators must obtain the greatest possible utilisation of expensive aircraft and that crew schedules must be integrated with the schedules of maintenance work, but much irritation and annoyance can be eliminated by the advance preparation of crew schedules and by adhering to them. Proper scheduling so that flight time is evenly divided, with as far as possible, no pilot assigned on successively long and tedious flights, can do much to keep fatigue at bay. Ensuring adequate messing and other facilities at outlying stations and keeping pre-flight duty and stand-by time to the minimum will also help. Furthermore, it is the operator's responsibility to ensure the thoroughness of all maintenance work, as a series of even minor mechanical difficulties can cause anxiety and uncertainty over the serviceability of the aircraft.

Since the present human design appears fairly static, with little evidence of a new, improved model, it would appear that aircraft design must bear the brunt of any innovations. Operators should co-operate with aircraft designers to achieve the best possible arrangement of instruments, lighting, heating and other flight deck details, endeavouring to eliminate unnecessary or difficult manoeuvres during flight. The simpler the task, the less fatiguing its performance. As visual requirements are so important, especially in this era of rapid closure and density of traffic, aircraft designers should endeavour to provide the best possible visibility together with such instrument grouping as might best lessen the visual strain upon the air crew.

Studies of transport pilot behaviour on routine flights has provided data on the best lay-out for controls. With existing systems it has been shown that many of the controls are as much as 15 inches beyond average finger tip reach, with the result that their manipulation requires considerable trunk movement causing bodily and visual displacement from the usual flight position. It was also pointed out in these studies that the working area of a single arm or hand is a semi-circular, rather than a straight, flat, area so that an arrangement of the control panel on a curve would be a considerable improvement. Since the possibility of human error during fatigue, emotion or physiological stress is ever present it is suggested that proper coding of controls by variations in position, shape, colour and size might reduce the likelihood of such error.

Operators already recognise the benefits of good ground services, with detailed meteorological briefings. This, together with available aids to navigation and landing, does much to alleviate anxiety and thus prevent fatigue. All these factors can help to prevent the incidence of fatigue and, together with frequent rest periods for recuperation, can do much to avert cumulative fatigue and aeroneurosis. It is pointed out in passing that a number of airlines are introducing airborne weather radar in their aircraft which enable the crews to identify and avoid areas of turbulence, lessening strain upon themselves and the aircraft and avoiding disruption of schedules.

Organisations such as the International Civil Aviation Organization, the International Air Transport Association and the International Labour Organization, as well as many pilot organisations, are all intensely interested in the problem and are endeavouring through their members to arrive at a satisfactory solution. As already noted, studies have produced so many variables that it is unrealistic to attempt to provide international regulations to cover all exigencies and there appears to be a considerable difference of opinion as to the right method of resolving the difficulties. Lack of quantitative units to measure fatigue has been a major stumbling block, but there appears to be a substantial measure of uniformity among States as to the ultimate limits of flight crew endurance which has resulted in the imposition of flight time limitations in many countries. There are, however, many who disagree that international standards are necessary, or even desirable, and who think that each State or operator is best left to make its own decisions and bear its own responsibilities.

The International Civil Aviation Organization (I.C.A.O.), studied the matter of flight fatigue at its First and Second Operations Division meetings in 1946 and 1947, and recommended the adoption of flight time limitations covering periods of one day, one week, one

month and one year. Although I.C.A.O. published these as Recommended Standard Practices and Procedures as early as 1946, later, in 1947, it was decided that they were not mature enough nor practicable for world-wide application. In their place a general standard placing the responsibility on the operator, through States, was adopted as follows:

> "An operator shall establish limitations on the flight time of flight crew members. These limitations shall be such as to ensure that fatigue, either occurring in a flight or successive flights or accumulating over a period of time, does not endanger the safety of a flight. The limitations shall be approved by the State of Registry."

Subsequent I.C.A.O. Operations meetings have again discussed the problem of flight time limitations, but it has not been possible to formulate more detailed standards in this respect and the general standard quoted above is effective today.

The objective of a limitation of flight time is to prevent such degrees of fatigue of crew members as to interfere with flying safety. In general, existing State regulations specify the maximum periods of time during which flight personnel may be exposed to conditions most likely to induce fatigue. These periods are variously expressed in terms of hours of duty, or hours of flight time and are generally supplemented by corresponding requirements for periods of rest. Regulations apply variously to the complete crew, the flight crew only, the pilots separately, other members of the flight crew separately and non-technical members of the crew. In spite of the variations between the provisions of existing regulations it appears that there is a large measure of agreement that the danger arising out of flight crew fatigue can be substantially alleviated by the imposition of flight time limitations.

Unfortunately this type of regulation, while halcyon in concept, fails to take into account certain economical truisms. To follow these regulations it is often necessary for the operator to station slip crews in inaccessible and frequently unhealthy spots, or to provide two, or even three, crews to an aircraft. The scheduling of air crew on long international flights exceeding flight time limitations makes it necessary for crews to lay over at a foreign base while a relief crew takes over the aircraft. This tends to make operations overly expensive and leads to curtailed services, increases in fares and freight charges, or cuts in salaries to crews. Many crews would prefer to exceed the flight time limitation by several hours in order to complete their flight at an airport with reasonable rest and recreation facilities, than adhere to the letter of the law and trans-ship at some small airport where facilities for rest may be practically non-existent. Crews are notoriously unprepared to spend any extra time away from their home bases and discontent arises when existing regulations necessitate their so doing.

The problem may perhaps be overcome by providing extra crew, but this is often limited by the design of the aircraft when no further crew space is available. Rest facilities might be provided aboard the aircraft for the crew after their elapsed time of duty, but this again poses a design problem as adequate facilities cannot always be provided, as pointed out in a recent accident report which reads in part: "A mattress is provided which is placed over the luggage in No. 3 Hold." In any case, it is doubtful whether adequate rest could be obtained on board, for the Captain at least, since if weather or other conditions present any difficulty he would doubtless wish to be at the controls. Faster cruising speeds of aircraft now in the design stage may have an effect on crew scheduling, since this speed might prevent the exceeding of flight time limitations on many routes now in excess of such limitations.

There has been a mistaken concept in many quarters that the only answer to air crew fatigue is to lessen exposure time by flight time limitation and a great deal of the attention of experts has been diverted into this area. Actually, the limitation of flight time and corresponding "on duty time" is only one of the many methods that can be employed to reduce fatigue. The whole aviation industry and its associations have been working, under the highest pressure, to improve the safety, regularity and efficiency of air navigation which, in effect, reduces the load on the air crew and goes a long way towards reducing fatigue.

During the past decade improvements in navigational aids, aircraft performance, automatic pilots, improved instrumentation, pressure cabins with air conditioned working quarters, better facilities on the ground for the crew, better meteorological forecasting and communications, among others, have reduced anxiety and relieved tension for crews.

In effect many of the variables influencing fatigue have already been removed, or greatly alleviated by international bodies in providing world-wide uniformity of equipment and aids and by the efforts of designers. The technical standards and recommended practices adopted by Member States of I.C.A.O. in the fields of communication, meteorology, rules of the air, operations, airworthiness, aerodromes, visual aids, licensing and training, have all helped to remove difficulties and lessen anxiety by providing basically the same air and ground facilities and procedures wherever the aircraft is flying.

The International Labour Organization, and the International Transport Worker's Federation, have been considering this problem and are actively engaged in studying flight crew fatigue, mainly from the social standpoint. Both of these organisations have been working in very close co-operation with I.C.A.O. on this matter and are at present studying the various regulations governing duty time and flight time limitation, with a view to world standardisation of duty time and the betterment of working conditions. The I.L.O. is studying the social problems at a meeting to be held later this year, when conditions of employment in civil aviation, hours of work of flight personnel and income security of flight personnel after retirement or grounding will be discussed.

The International Air Transport Association, the International Federation of Air Line Pilots, and many other similar organisations on the national level are

also vitally interested and have studied the problems and made recommendations.

From the foregoing it will be obvious that the problem of fatigue has received a great deal of consideration and nations, principalities and powers, not to mention pilots and operators, have all contributed towards a solution. It is hoped that this paper will help all concerned to appreciate each other's difficulties and even, perhaps, convert those who feel that fatigue is an illusion rather than a problem, in order that an even greater co-operation may result among them.

The findings of the Civil Aeronautics Board in the case of the accident to the European air liner provide several interesting and pertinent pointers on fatigue in air crew and it is proposed, in conclusion, to allow these facts to speak for themselves. It should be noted that this aircraft carried a large crew complement, a Captain who had made 150 Atlantic flights, 75 into Idlewild Airport, three other pilots, a radio operator and two flight engineers, as well as cabin staff. It would be reasonably assumed, therefore, that excessive duties were not undertaken by any individual. However, as the Civil Aeronautics Board report states:

> "Company officials testified that on a normal North Atlantic flight the Captain and one of the other pilots would fly the aircraft to Shannon and then would rest during the Atlantic crossing while the other pilots flew the aircraft. After reaching the more congested areas of the United States the Captain again would take control until the flight terminated. This procedure afforded each pilot nearly equal rest periods. The bunks on board the aircraft provided them with the best rest possible considering it would be under flight conditions and with continuing respective responsibilities for the flight.....
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> .....
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> .....There is no reason to believe that normal rest procedures were not followed. It is nevertheless believed fatigue was a factor in this accident. It was not only present as a result of the time en route approximately 22½ hours, but mostly a result of the additional extended 2½ hours period devoted to the four approaches and the high mental and physical demands made upon the pilots. The element of fatigue is strongly suggested especially during the last approach. Fatigue is evidenced by the pilot's poor adherence to the localizer path, the last descent to a very low altitude before the sharp pull-up, and the evidence of abrupt control action. It may also be noted to some degree in the pilot's slow response to the wind shift and the probable loss of airspeed which caused the sinking descent before the aircraft struck the pier. These factors lend credence to the belief that the pilot's efficiency and normal ability were seriously impaired by fatigue."

Some Problems in Aerodynamics and Their Solution by Electrical Analogy

by

D. KÜCHEMANN, Dr.rer.nat.
(Royal Aircraft Establishment)

and

S. C. REDSHAW, D.Sc.
(Professor of Civil Engineering, University of Birmingham)

Some purely aerodynamical phenomena, which might profitably be investigated by means of electrical analogue computors, are described. No attempt has been made to furnish a complete catalogue of problems but rather to present current issues, the solution of which would aid the development of practical aerodynamics.

Consideration has only been given to those questions which can be solved more suitably by an analogue computor rather than by a digital machine, although the feasibility of partially solving certain of them by the use of an analogue computor, and completing the work with a digital machine, is mentioned.

In scope, the survey includes two and three dimensional aerofoils as well as interference and a number of special problems.

The relative merits of the various forms of analogue computors are not extensively discussed.

1. Introduction

This note deals briefly with some purely aerodynamical problems which might profitably be investigated by means of electrical analogue computors. It does not attempt to provide a complete list of conceivable problems; instead, the problems mentioned are what might be called current issues, that is questions which have arisen out of current work and upon the solution of which the further development of practical aerodynamics will depend to some extent.

This note only includes those problems which, it is thought, can be solved more suitably by an analogue computor than by a digital machine. There may be a number of cases where it might be most profitable to find a reasonable first approximation with an analogue computor and subsequently feed this into a digital computor to find better approximations. Such methods of combining the potentialities of both computor systems are not considered here.

No attempt has been made to compare the two principle forms of electrical analogy, the electrolytic tank and the electrical network. Both these analogue computors possess advantages and disadvantages; a network will only provide an analogy to the finite difference form of the differential equation it is required to solve, as it is only possible to read the potentials at the discrete points provided by the nodal points of the net, whereas the tank provides a direct analogy to the continuous solution. Therefore, in cases where curved boundaries and special shapes are involved, unless a net with a very fine mesh is available, the use of a tank is often preferable to a net; but, on the other hand, if a number of independent potentials have to be set up at various points in the field under consideration the net is to be preferred to the tank. In general, the technique of using a network, providing it is non-reactive, is far simpler than that which has to be employed for an electrolytic tank.

Some cases are described, which are concerned with only partial problems. The solutions and results are then intended to be used within the framework of an ordinary numerical calculation method; such cases are included in the belief that it cannot be the sole purpose of computing machines to amass numerical data, for the digestion of which we are, in many cases, still quite unprepared, but to assist in the physical understanding by solving typical cases, on the one hand, and to furnish partial solutions, on the other hand, for what is otherwise a numerical " slide-rule " method of reasonable generality.

2. Two-Dimensional Aerofoils

The method of using the electrical analogy for the study of Laplacian flow fields* goes back in its essentials to Kirchoff[1], 1845. Since its earliest practical use by

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*The analogy itself is not described here. Nearly all the reports listed, which give results from analogue computors, also include a description of the theoretical background of the method. A recent summary report by Dadda[4], 1951, can serve as a brief introduction to some of the techniques employed as well as to its various applications to magnetic fields, filtration and diffusion movements, elasticity, flow and temperature fields. Sander, Oatley and Yates[5], 1952, report on the application of the electrolytic tank to problems of electron optics.

Lazzarino[2], 1923, and Relf[3], 1924, and its subsequent refinement by Pérès and Malavard[6-10], 1932-1947, and others[11-13], the electrolytic tank has been applied to the solution of finding the incompressible potential flow around two-dimensional aerofoils, including the effects of circulation. At the same time, considerable progress has been made in the analytical treatment of this problem, and it is probably fair to say that the numerical calculation of the velocity over the surface of any given conventional aerofoil section (for instance, by the method of Weber[14], 1953) is now so simple and at the same time so accurate that the application of an analogue computor is not really worth while. These calculation methods give only the velocity along the surface; they cannot be extended easily to the calculation of the whole flow field and it is here that the analogue computor comes in. There are cases where the velocity field and the streamlines outside the aerofoil are required, for example, in interference problems such as the determination of the properties of bodies in the flow field of the wing, and the analogue computor appears to offer the simplest means for solving such problems.

Taylor[15], 1928, and Busemann[16], 1937, proposed methods for using an electrolytic tank for solving flow problems in compressible fluids, and Vandrey[17], 1944, simplified and refined the method. It does not appear that much use has been made so far of this possibility. In view of the large number of conflicting " rules " for relating incompressible and compressible subcritical flows to one another, and in view of the paucity of known solutions of sufficient accuracy and of reliable wind tunnel results, it appears to be worth while to reconsider the use of the tank for obtaining a number of solutions of sufficient accuracy to check the reliability of the various approximate rules. It is also of interest to note that Kron[18], 1945, has designed an electrical network for the solution of the problem. Kron's network requires the use of reactive components with the attendant trouble that it is expensive and difficult to provide enough closely matched units to give a network having sufficiently fine mesh. Possibly for this reason little or no experimental results are available, except for a brief report by Carter and Kron[19], 1945. Nevertheless, the technique is an interesting one and it would probably be worth while investigating it further.

Solving flow problems by means of an electrical network is closely related to the numerical solution of such problems by means of Southwell's relaxation method[20], 1946, or Thom's squares method (*see* Ref. 21, in which references to Thom's earlier work can be found). For practical purposes, a combination of the analogue computor with the method of Thom might be suggested. When problems of compressible or viscous flow are calculated by this method the potential flow field is first determined and the incompressible streamlines and equi-potentials are then used as grid for the further calculations. These preliminary calculations could conveniently be carried out by an analogue computor. The network is better suited in these cases since the subsequent calculations are also based on the difference equation.

The argument is often advanced that results from the analogue computors, being solutions of Laplace's equation, are of little practical use because the important viscosity effects introduced by the boundary layers are ignored. Apart from the fact that a knowledge of the inviscid flow is always a great help in assessing the nature and the magnitude of the viscosity effects, it should now be possible to include boundary layer effects in an electrical analogy by investigating an analogous inviscid flow where boundary layer and wake are suitably represented. This method, due to Preston[22], 1949, of reducing the problem of calculating the viscous flow past an aerofoil with wake to a potential flow problem, has now been brought to a stage by Spence[23], 1952, of sufficient reliability and accuracy for practical purposes, as shown for instance by the cases treated by Brebner and Bagley[24], 1952. However, only a few examples have been worked out so far, and it would be very valuable to compute charts, for immediate application in this case, giving the two-dimensional lift slope, the drag coefficient and the position of the aerodynamic centre for a number of modern aerofoil sections as a function of Reynolds number. At present, there are only empirical and not really reliable charts for the lift slope and the well-known profile drag curves of Squire and Young[25], 1937, which have been derived for only a few aerofoil sections which are no longer representative of current practice. In view of the extraordinary usefulness which the curves of Squire and Young have shown, a new and complete set of charts should be of great practical value.

In connection with thin and swept wings, more interest is now being taken in the flow past aerofoils with local flow separation (*see e.g.* Küchemann[26], 1953). To understand the flow phenomena, some flows must first be studied in two dimensions. Experimental evidence suggests that, for such types of flow as occur frequently in practice, the flow may be envisaged as being primarily inviscid but with limited dead-air regions attached to the aerofoil. The dead-air regions are separated from the mainstream by vortex sheets and are closed at the rear end, if at all, by a streamline with a pressure rise due to turbulent mixing. The constant-pressure part of the bubble is followed by a thick boundary layer and a wake, the displacement thickness of which remains roughly constant. The pressure inside the bubble varies with the angle of incidence, and with it the geometry of the bubble. This simplified concept of such flows makes them capable of being treated by analogue computors, and it would appear to be well worth while investigating the practical implications of carrying out a more detailed study of this problem. A similar problem occurs with aerofoils with flaps or spoilers with dead-air regions. There are some analytical methods for treating such problems, for instance by Schmieden[27], 1940; Walz[28], 1940; and more recently by Woods[29], 1953. But the numerical evaluation involved normally forbids the working out of many examples so that a survey, to show what are the

important features of such flows, is not likely to be obtained from these methods.

It would be desirable to investigate the suitability of analogue computors for the study of flows with free streamlines. This is a problem which is of general interest in fluid mechanics, arising as it does also in connection with the design of hydraulic machines, and also with regard to the problem of calculating non-homenergic flows, such as the flow past an aerofoil with a jet issuing from it. At least for incompressible fluids, a non-homenergic flow can always be reduced to an equivalent homenergic flow, as shown by Küchemann and Weber[30], 1953; this in turn can be treated by an analogue computor. Since neither the shape of the boundary nor the pressure distribution along it are known beforehand, a solution normally involves an iteration process where it is very important to begin with a good first approximation if the calculation is carried out by ordinary numerical means or by a digital computor. Here the analogue computor has a great advantage in that convergence can be assured more easily.

Closely related to the last problem are those concerning aerofoils with sucking or blowing. In either case, the primary object may be to influence the boundary layer but this aim is often achieved by first modifying the pressure distribution to control the boundary layer development; for example, to avoid flow separations. This effect of sucking or blowing can be treated by analogue computors. A brief note by Matsunaga[31], 1954, is of interest in this connection. If sucking and blowing are combined in one ducted aerofoil, as proposed by Küchemann[32], 1954, the flow pattern is complicated and difficult even to imagine, let alone to treat analytically. In the development of such aerofoils, the electrolytic tank and the electrical network could be a great help.

3. Three-Dimensional Aerofoils

The method of investigating the properties of three-dimensional wings in an electrolytic tank has been developed by Pérès, Malavard and Duquenne[7, 33, 34]; it can be applied to either thick wings at zero lift or thin wings with lift, using the assumptions of linearised theory in both cases*. Campbell[35], 1949, has also discussed the electrical analogies for use with the electrolytic tank in connection with the determination of the pressure distribution over a lifting surface, but he has not published any results. Redshaw[36, 37], 1951 and 1954, has designed and experimented with an electrical network for solving the same problems and has obtained solutions to a number of examples of practical importance. The pressure distribution over thin twisted cambered wings may also be studied by this method and, by using Jones' method[38], 1948, of representing a thick aerofoil by a cambered surface, the study of thick wings could be included. By using an affine transformation, results applicable to compressible subsonic flow may be obtained.

*This apparatus has been further developed by L. Stenström[83], 1950, who measures directly the potential gradient.

Regarding thickness effects on wings of finite aspect ratio, some work remains to be done on the changes in the pressure distribution as the aspect ratio becomes small and how these changes are affected by sweep and taper, both in plan form and thickness. We may expect some results soon from an analytical approach by Newby and from a systematic series of calculations, performed on the ACE, by Neumark. However, the applicability of the results will be limited in both cases by the particular choice of the aerofoil section shapes which must be chosen to keep the computing work within reasonable limits. Moreover, this is a case where the analysis of the results, after the computing has been done, is especially difficult. Some other cases are now being treated by Malavard in his electrolytic tank and the advantages of this method are particularly obvious in this case in that any given section shape can be computed once a model of a given plan form has been made. This characteristic of the analogue computor opens up the following interesting prospect. It is now fairly clear that a wing of given plan form should be fitted with its own suitable aerofoil section and not with one that has been designed independently—for instance, because of its desirable properties as a two-dimensional aerofoil, as indeed all aerofoils have been designed nowadays. Each wing demands its individual section shape which will, moreover, vary along the span and will depend on the special purpose for which the wing is designed, for example, low drag at high speeds. In other words, for wings of small aspect ratio as also for swept wings, the concept of a " section shape " loses its significance and should be replaced by the concept of a thickness distribution over the whole wing. The analytical determination of such an integrated shape for a given pressure distribution, say, is so complicated as to be practically impossible, if the aspect ratio is small and the wing tapered in plan form and thickness. But to solve the problem by an analogue computor should be very simple; indeed, the tank or the net are ideally suited for it.

Similar considerations apply to the distribution of lift over the surface of such wings. Again, one should not choose a plan form, leave the section symmetrical, and await the resulting lift distribution; instead, the lift distribution should be adjusted to suit the particular plan form, in the last resort, in order to give a desirable pressure distribution for the thick wing at lift. This means that the wing must be cambered and twisted. Again, the tank fits this task perfectly and the same model could, in fact, be used as that for determining the thickness distribution. Some preliminary tests on these lines are at present being undertaken by Malavard. The possibility of using a network for this purpose must not be overlooked because of the advantages a net has over a tank in experiments which require the setting-up of a number of individual potentials, such as would be needed in this instance.

A simple method for calculating cambered and twisted swept wings has been developed by Brebner[39], 1952, but it is applicable to wings of moderate and large aspect ratio only, in subsonic flow. Cambered wings in

supersonic flow have been treated by Roper[40], 1950, but the numerical evaluation is complicated. Some work remains to be done to fill the gap. The special case of wings at sonic speeds is at present being investigated by Mangler, using as a basis the slender-wing theory of R. T. Jones[41], 1946, which is applicable to wings at sonic speeds as well as to wings of infinitely small aspect ratio in incompressible flow. A substantial part of the work involved in this theory is to relate the induced incidence from the system of trailing vortices to the spanwise distribution of the vortex strength. According to this theory, this problem can be reduced to that of a two-dimensional flow in planes normal to the mainstream past the sections of the wing in these planes. For a cambered and twisted wing, the shape of the wing in these planes is different for each chordwise station, and it is this multitude of two-dimensional flow problems, in themselves simple, which sets up a formidable computational task. It would appear that the analogue computor is a convenient means of mastering this work.

It is, of course, also of some interest to compare results from an analogue computor for ordinary plane lifting surfaces with those obtained from the various existing theories, in view of the still apparent uncertainty as to which method is the most reliable. It has not yet been possible to obtain an estimate of the errors involved in any one theory by mathematical means, and comparisons between the results from theory and from experiment suffer from the drawback that most theories are not capable of taking account of thickness and viscosity effects. The analogue computor, on the other hand, sets out to do precisely the same thing as most of the theories.

With reference to Falkner's vortex-lattice theory[42], 1943, W. P. Jones[43], 1946, proposes to measure the normal magnetic force of a system of horse-shoe shaped circuits as representing the downwash of a system of vortices. This is an interesting example of how an electrical analogy can be used especially to suit a particular theory.

The loading on swept wings with flaps is a special problem which has not yet been solved adequately although its existence has been realised for some time. The difficulties associated with a complete analytical treatment are very great, and the analogue computor promises to be of valuable assistance. Malavard has begun some tests on these lines and earlier work of his is reported in Ref. 34. This problem provides an interesting case of demonstrating how the analogue computor can be applied to solve not the complete problem, but a partial problem within the framework of an existing general theory. The difficulties in this particular case lie only partly in determining the sectional lift slope and the induced downwash from the trailing vortex system, at any spanwise station; these quantities can be taken, to a first approximation, from the theory of Küchemann[44], 1952. The main unknown effect of the flap is how it changes the sectional zero-lift angle of incidence and the zero-lift pitching moment, and it is suspected on theoretical grounds that these two quantities depend on the angle of sweep of the wing and on the spanwise position of the section considered, so that the values derived by Glauert[45], 1927, for two-dimensional aerofoils cannot be applied. This approach provides a simple way of analysing the data from an analogue computor, which will be used to calculate the spanwise distribution of lift and position of the aerodynamic centre for a given flap geometry; the existing theory will then be used to find out what the change of zero-lift angle and pitching moment must have been to produce these results, and it is hoped that it will be possible to draw charts showing the change of these two parameters with sweep, spanwise position and, possibly, the aspect ratio of the wing. These charts in conjunction with the general theory can then be used to calculate, with some confidence, the properties of any given wing with flaps. At any rate, it is not necessary to attempt to compute the properties of all conceivable wing-flap arrangements, varying the numerous parameters in such a way that any particular case can be interpolated.

The use of electrical analogies for solving problems involving oscillatory surfaces has been suggested by Landahl and Stark[46], 1953. In three-dimensional incompressible inviscid flow this is achieved by means of the acceleration potential which may be used for determining the pressure distribution on lifting surfaces which have twist and camber. Landahl and Stark used an electrolytic tank to measure the force and moment coefficients on a two-dimensional wing oscillating in vertical translation and pitch. Similar experiments are being carried out by Palmer at the University of Birmingham using a resistance network to determine the suitability of the method. The boundary conditions which would be difficult to apply on a tank would be much easier to set up on a network, but a fine mesh in the vicinity of the aerofoil appears to be desirable when using the acceleration potential analogy.

Further problems of three-dimensional aerofoils, which can possibly be solved most conveniently by analogue computors, concern the effect of the boundary layer on the forces on three-dimensional and, in particular, swept wings; and also the effect of tip and part-span vortices, which arise when local flow separations occur somewhere (*see e.g.* Ref. 26). It would appear that most of these problems can be treated with some hope of success only after the corresponding problems on two-dimensional wings, already mentioned, have been sufficiently elucidated.

4. Interference Problems

Analogue computors have been used frequently in the past to solve interference problems which are notoriously difficult to treat analytically. A typical case is the study of aerofoils in cascade, which was done by Malavard and Siestrunck[47], 1945; de Haller[48], 1947; Hargest[49, 50], 1949; and Revuz[51], 1954. It appears that some work on this problem, in particular on arrangement corresponding to turbines, is still required.

Another class of problem concerns the loads on combinations of lifting surfaces and bodies, such

as wing-fuselage arrangements. Using the concepts developed in Ref. 44, it is quite simple to estimate the effective incidence as induced by the bound vorticity components of the lifting system, including the effects of aspect ratio, sweep, taper, and so on. However, a fair amount of numerical work is involved in determining the induced incidence from the system of trailing vortices. According to Ref. 44, this latter problem can always be reduced to that of a two-dimensional flow, in planes normal to the mainstream, past the wake contour if the aspect ratio is large (Trefftz plane) or past sections through the actual wing-body combination if the aspect ratio is small (Jones plane). For wing-fuselage combinations, such theories have been developed by Weber, Kirby and Kettle[52], 1952, for large aspect ratios, and by Spreiter[53], 1949, and Adams and Sears[54], 1953, for small aspect ratios. In many cases, it is sufficient to perform the actual work only for such arrangements as give minimum induced drag, which simplifies the analysis considerably since the wake contour can then be considered in a uniform stream. Here is another typical case where only a partial problem is solved,—for instance, very simply, by means of a simple two-dimensional pure resistance network,—the results of which are then incorporated into a more general calculation method which is so simple that it does not require computational aids.

So far, these problems have always been solved by using conformal transformations which reduce the wake contour to a simple shape, such as a slit or a circle. But this involves a considerable numerical effort if the wake, or wing, contour is not in itself simple. Examples are the work of Hartley[55], 1952, on wings with tip tanks (two circles representing the traces of the tanks, leading to doubly connected regions); the work of Owen and Maskell[56, 57], 1951, on slender wing-body-tailplane combinations; and the work of Weber and Hawk[58, 59], 1952 and 1954, on fin-body-tailplane combinations in a sidewind. Several other cases could be mentioned, which are of considerable practical interest, and where the numerical work would become prohibitive so that the solution by an analogue computor would be advisable. For example, in the case of tail unit combinations, the cases considered so far of a pure sidewind do not yet represent what really happens in practice since there will always be an angle of incidence as well as a sidewind. Again, the method used for calculating tip tanks could be extended to include nacelles within the wing span, and also asymmetrical arrangements which, of course, would complicate the numerical analysis a great deal but not the analogue computing. This approach has actually been used by Falkner and Gandy[60], 1946, who investigated the lift on wings with fins, or endplates, by means of results from Malavard's tank. This however, is a case where the analytical treatment is relatively simple as has been shown by Küchemann and Kettle[61], 1951, who used the theory of Mangler[62], 1939.

Closely related to these problems is the calculation of the pressure distribution at any Mach number and of the supersonic drag of slender wings or wing-body combinations (*see e.g.* Ward[63], 1949; Adams and Sears[54], 1953; Weber[64], 1954). Again, the knowledge of an incompressible potential flow in planes normal to the mainstream is required and the use of an electrical analogue computor should be profitable in all those cases where the cross-sectional shape of the given body does not lend itself easily to an analytical treatment.

5. Various Special Problems

There is a great variety of potential flow problems which have already been treated by means of analogue computors, and the list could probably be extended. A very ingenious application has been made by Siestrunck[65], 1944, to determine the effect of the helical vortices of a propeller with a finite number of blades; and a d.c. network analyser has been used by Concordia and Carter[66], 1947, to determine the flow pattern in a centrifugal impeller. Wind tunnel corrections have been worked out by Pérès and Malavard[67], 1945, and axi-symmetric contraction shapes suitable for wind tunnels have been studied by Babister, Marshall, Lilley, Sills and Deards[68], 1951, as well as by Hubbard[69], 1949. Bodies of revolution and axi-symmetrical diffusers have been investigated by Cheers, Raymer and Fowler[70], 1945, and again by Lewis and Newman[71], 1945 and Cheers and Raymer[72], 1946. Axi-symmetric cowlings and air intakes have been treated by Lewis and Newman[73, 74], 1944, and by Hahnemann and Bammert[75], 1946. A number of investigations concern the movement of water when it seeps through under hydraulic structures and the uplift pressures under dams and weirs caused by this; *see* among others, Puppini[76], 1922; Pawlowsky[77], 1922; Ram, Vaidhianathan and Taylor[78], 1935; Gentilini[79]; 1946; and Dolcetta[80], 1949.

McCann and Wilts[81], 1949, use an electric network for problems of heat transfer and fluid flow, which obey equations other than that of Laplace. They discuss the range of application of analogue computors and, in particular, viscous damping in small-diameter tubes, the temperature distribution in a gas-turbine rotor and an analogy for compressible fluid flow. A d.c. network analyser for solving wave-equation boundary-value problems has been described by Swenson and Higgins[82], 1952.

It may be mentioned that, in some cases, the flow in the hodograph plane may be treated instead of the flow in the physical plane. This has been done, for instance, by Busemann[16], 1937, and by Vandrey[17], 1944, for the case of compressible flow. It may be possible to treat other problems in a similar manner. The analogue computor is preferable to an analytical treatment here, particularly if the hodograph contains overlapping regions.

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Fatigue Aspects of Structural Design

by

W. A. P. FISHER, B.A., A.M.I.Mech.E.

(*Royal Aircraft Establishment*)

Introduction

The problems associated with the fatigue life of aeroplane structures have been so thoroughly discussed by experts of international repute that it is with some trepidation that the present speaker ventures into this difficult and controversial field. However, the need for more experimental fatigue data on actual structural components (as distinct from idealised test specimens) is undeniable; further, it is hoped that the present paper may stimulate discussion. Opinions expressed in this paper are the author's personal views, and do not necessarily reflect the policy of the Ministry of Supply.

A comprehensive bibliography on this subject has been given recently by Lundberg in the 18th Wright Brothers' Lecture[1].

In view of the many uncertainties affecting a predicted "safe life," it is not surprising that many authorities, Mr. Lundberg included, favour the "fail safe" principle of design. The "fail safe" philosophy postulates that some aeroplanes of a given type will sustain fatigue cracks in the primary structure before completing their service life, and that cracking may lower the static strength factor below a safe level before it is detected unless sufficient strength is provided by alternative paths. In practice, the "fail safe" principle means the deliberate adoption of a statically indeterminate structure. If a part of the structure begins to crack, it is then able to shed some of its load, and the rate of crack propagation becomes non-catastrophic.

The long service lives of many DC-3 aircraft can be attributed not to freedom from fatigue, but to the fact that cracks in the wing joint were not catastrophic owing to the multiplicity of attachment bolts and the 3-spar construction. Hence, replacement and strengthening of the outer wings after completion of their useful fatigue life enabled these aircraft to continue for very many years at a high utilisation rate. Even inner spar booms, as in the Viking wing, have been replaced, the double booms having, fortunately, prevented catastrophic failure due to fatigue failure of one half boom. But it would be inconvenient, to say the least, to adapt a shell-type construction for inner spar replacement, and the pertinent decision is whether to design for assembly replacement, for component replacement, for crack detection and repair, or for a safe life as long as the commercial life of the aircraft. The term 'safe' is here interpreted as less than 0·1 per cent. probability of catastrophic failure by fatigue.

Lundberg[2] has written "I was pleased to hear Mr. Schleicher's opinion that the idea of exchanging shear and bending material is economically impracticable in shell-type constructions. For future airplanes, it seems more rational to design various components for different service or limit lives. Such items as the fuselage and wing center section would then be designed for the limit life of the airplane and repairs of these items would be of a minor character and rather exceptional."

If this view be accepted, it follows that the pressure cabin and the inner wings must be designed to the life of the aeroplane, whether the "fail safe" principle be adopted or not. To do this in the early design stage, the designer must have available as much fatigue test data as possible in the form of *P-S-N* curves, *i.e. S*-log *N* curves for a given failure probability.

This paper will not attempt to cover more than the design of wings for civil transport aircraft, since the fatigue strength of pressure cabins is greatly dependent on detail design and, for obvious reasons, statistical fatigue data on pressure cabins is scarce. Moreover, pressure cabin fatigue has been discussed in a recent paper by Dr. P. B. Walker.[3]

In former days, for lack of gust load data, the designer of civil transport aircraft had to be satisfied with developing the best spar design possible and hoping that it would give an adequate safe life. Now that much accelerometer data has been accumulated, it is becoming possible to forecast the average gust spectrum for a new aircraft on a specific route. Thus, using generalised endurance curves for wing tension booms, the designer may now estimate in the early design stage the number of safe flying hours he will be able to offer. By limiting the ultimate design stress for the tension booms, by judicious choice of material, and attention to detail design the safe life for the wings can be controlled in advance.

There are two critical types of cross section in a spar boom which must be considered independently because their endurance curves are of quite different form. These are:—

1. The spar joints.
2. The spar boom with holes.

Spar Joint Curve

Figure 1 shows *S*-log *N* plots for a variety of aircraft joints differing greatly in design, based on the net area at the section of failure of the aluminium alloy spar boom. Some of the joints are consistently better than others, and the two curves represent a failure probability of 10 per cent. for an average joint in extruded alloy to D.T.D.363A and 364B respectively. When it is considered that far less attention was given in the past to the design of joints for long fatigue life, one may

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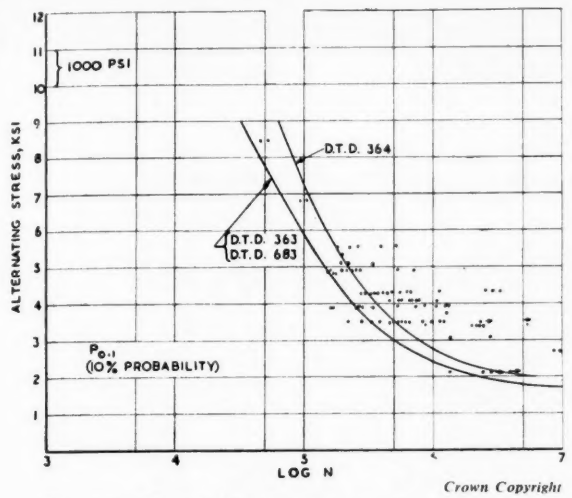

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FIGURE 1. Generalised endurance curves for spar joints. (K.S.I. denotes kips/in.^{2} where a kip is 1,000 lb.)

reasonably suppose that any future joints will be, if anything, better than these curves indicate, and therefore these generalised 'spar joint' curves are probably conservative. As the mean stress in the majority of the tests was between 12,000 and 15,000 lb./in.^{2} on net area, the generalised curves should be taken as applying to a mean stress of 13,500 lb./in.^{2}

Correction for Mean Stress

The order of correction required for mean stress can be estimated from Fig. 2 which shows the endurance curves for test specimens in the form of a flat bar with a single hole loaded through a push-fit steel pin. Mean stresses for the two curves were 5T/in.^{2} and 7.5 T/in.^{2} respectively. For alternating stresses between 3,000 and 7,000 p.s.i. the endurance varies inversely as 1.15 times the mean stress. A rough rule commonly used is to factor the endurance at a given alternating stress inversely as the mean stress.

Spar Boom with Unloaded Flange Holes

Spar booms are normally machined to a Tee or a Channel form, and have holes drilled in the flanges for connecting to chordwise members.

The endurance of these booms, to failure through a flange hole seems to depend more on the material properties than on the shape of the cross section, except that practical spar boom sections give substantially lower results than round bars with transverse holes. The latter are therefore unsuitable as idealised test specimens, and some other form of test bar is necessary for the purpose of extensive laboratory tests.

Figure 3 shows endurance plots for a channel section, diagram 2, and the Tee section, diagram 3 in the upper right-hand corner. The material specification was D.T.D. 363A for both. In both cases the test specimens were anodised. Two curves are shown. The upper curve is a mean curve for notched bars, as in diagram 1, also made from D.T.D. 363A, but unanodised. The mean stress was constant at 14,500 lb./in.^{2} It is to be noted that these side notches were designed to give a theoretical stress concentration factor K_t of 3.25. Making due allowance for the mean stress, this curve (which is a mean, or 50 per cent. probability curve) fits reasonably with the results for the channel and tee sections. The lower curve is an estimate of 10 per cent. failure probability for the spar booms in D.T.D. 363A (*i.e.* high zinc type) for comparison with the spar joint curve shown in Fig. 1.

Choice of Material

It is at this stage that the choice of material enters into consideration. Tests, both of spar joints and of "notched" specimens indicate a lower mean endurance (though possibly lower scatter) for the high strength zinc alloys than for the L.65 or the 24 S-T class of alloys. On this account, the trend in the U.S.A. has been away from the high-strength zinc type alloys. Curves derived by Lundberg[4] through statistical treatment of test results on notched laboratory specimens indicate a life

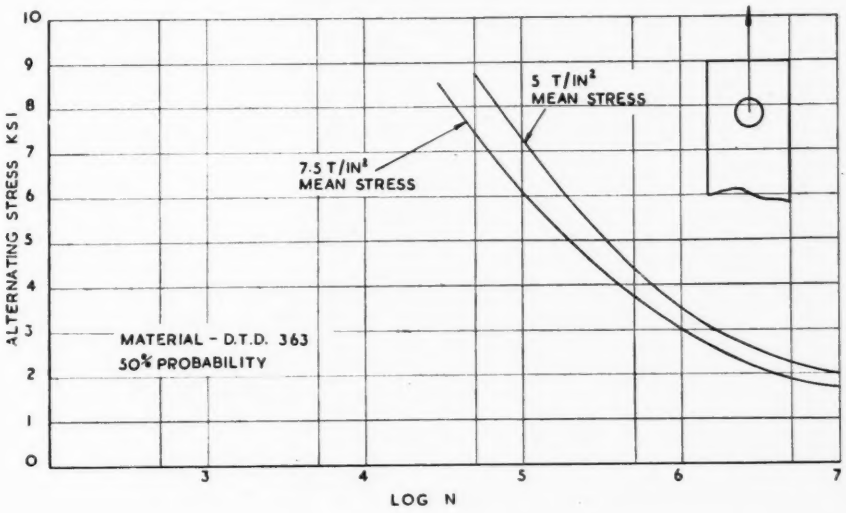

FIGURE 2. $S-\log N$ curves, loaded holes—push fit.

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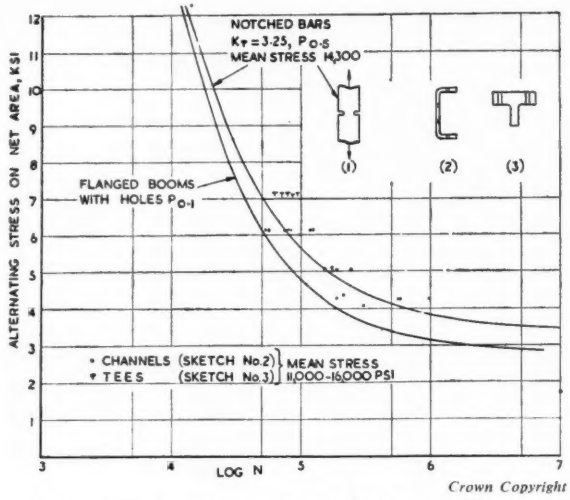

FIGURE 3. Endurance curves for notched bars, spar booms.

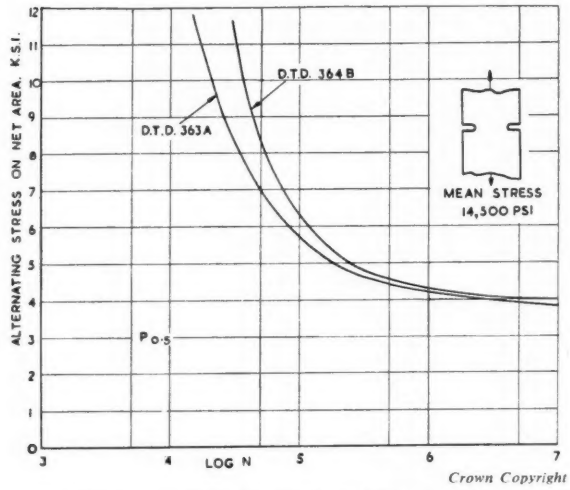

FIGURE 4. Stress concentration factor $K_t = 3{\cdot}25$. Comparison between D.T.D. 363 and 364.

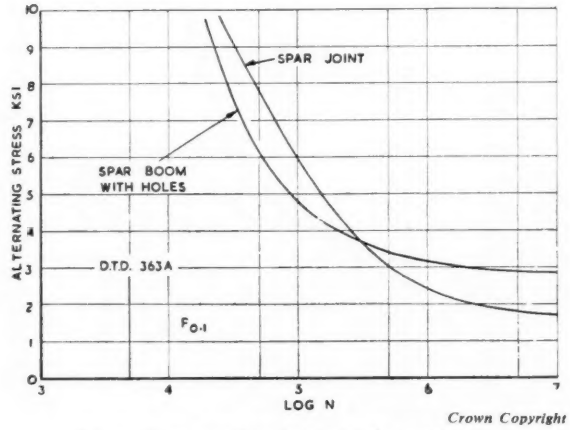

FIGURE 5. Comparison between joint and boom.

for 24 S-T specimens 10 times as great as that for 75 S-T specimens of identical form. A smaller, but still significant, difference between the British alloys, specifications D.T.D. 363A and 364B, is indicated in Fig. 4, the specimens being of the same side-notch design as in the previous figure. Accordingly, when fatigue considerations limit the ultimate design stress of the tension booms to well below the U.T.S. of the material, it is advantageous to use the non-zinc type of alloy.

A further point with regard to material properties may be mentioned here. There is a growing body of evidence that, in test specimens which are jointed or notched, and tested with a realistic loading cycle for spar booms, the lower the ratio of 0.1 per cent. proof stress to ultimate stress the longer is the endurance. Thus the fatigue behaviour of materials in a structure can vary with the condition of the material in a manner not indicated by simple Wohler tests. The author believes that the plasticity—or, rather, the plastic range—of materials is of great importance in the fatigue of structures.

Comparison between Spar Joint and Flange Hole Curves

Figure 5 shows the spar joint curve and the flange hole curve for zinc alloy D.T.D. 363A superimposed. The difference in shape is obvious. Whether failure will occur first at the joint or at the flange holes will depend on the relative static reserve factors and on the level of alternating stress. For equal net areas the joint appears to be better at high alternating stress, but worse at low alternating stress.

Choice of Ultimate Design Stress

Attention has already been drawn in a Report[5] by the author to the qualitative improvement in life resulting from a reduction in the ultimate design stress for the 50 ft./sec. gust case in the tension booms, *i.e.* by introducing a 'fatigue factor' in static design. Because the stress cycle amplitudes due to lesser gusts are proportional to the 50 ft./sec. gust stress increment, the U.D.S. is easily the most important parameter by which the designer can extend the designed safe life.

Statistical Treatment for Scatter

When a large number of tests is made under identical conditions, the distribution curve, or histogram, of the logarithms of the endurances approximates to a normal, or Gaussian distribution. When drawing a mean *S*-log *N* curve by eye from plotted test results at various alternating stresses, a symmetrical distribution in log *N* is tacitly assumed.

If X tests are made under identical loading conditions, the mean log value, $\log N_M$ is $\frac{1}{X} \Sigma \log N$.

Thus N_M, the antilog of $\frac{1}{X} . \Sigma \log N$, is the Geometric Mean Endurance.

Figure 6 shows distribution densities of $\log N$ for two different types of specimen called *A* and *B* respectively, and distribution density curves calculated on the assumption of "log normal" distribution are drawn. For type *A* the scatter is relatively small, and the standard deviation σ for $\log N$ is 0.112.

If $N_{n\sigma}$ denotes the endurance whose logarithm is $n\sigma$ less than N_M, we have by definition

$$\log N_M - \log N_{n\sigma} = n\sigma$$

whence $$\frac{N_M}{N_n} = (\text{antilog } \sigma)^n = (F_\sigma)^n$$

where $F_\sigma = \text{antilog } \sigma$ and is termed the "standard deviation factor," a convenient measure of scatter.

For specimen type *A*, $F_\sigma = 1.3$ and for the more scattered results shown by specimen type *B*, $F_\sigma = 1.8$.

Figures compiled at R.A.E. from Australian tests on Mustang wings at different alternating loads show a variation in F_σ from 1.62 for $N_M = 250{,}000$ cycles to 1.05 for $N_M = 5{,}000$ cycles.

In Fig. 7 is shown a Gaussian density curve for $\log N$, the geometric (or mean log) value N_M occurring at the middle of the symmetrical hump. Deviations of + and $-\sigma$, 2σ, and 3σ are shown. At any endurance *N*, the probability of failure is the ratio of the area under the curve to the left of the log *N* ordinate to the total area under the curve. From tables based on the Gaussian distribution, it can be shown that for a failure probability of 0.1

$$\log N_{0.1} = \log N_M - 1.28\sigma,$$

and for a failure probability of 0.001

$$\log N_{0.001} = \log N_M - 3\sigma \quad \text{(approx.)}.$$

$$\text{Thus } N_{0.1} = \frac{N_M}{(F_\sigma)^{1.28}}$$

$$\text{and } N_{0.001} = \frac{N_M}{(F_\sigma)^3}$$

giving the relation $$\frac{N_{0.001}}{N_{0.1}} = \frac{1}{(F_\sigma)^{3-1.28}} = F_\sigma^{-1.72}$$

The interpretation of Fig. 7 will be clearer if we plot hypothetical probability curves on an *S*-log *N* chart for an assumed value of F_σ.

Figure 8 shows the probable number of failures out of 1,000 specimens tested at fixed mean load assuming that the same standard deviation factor F_σ applies to all levels of alternating stress. The probability factors shown are: 0.001, 0.1, 0.5, 0.9 and 0.99, labelled respectively 1, 100, 500, 900, and 999. The 500 curve is, of course, the mean curve as normally drawn to represent a series of plotted test results, but in this instance is a hypothetical one. Constant F_σ implies a constant endurance ratio for a given probability, and therefore a constant interval between each curve and the next measured parallel to the log *N* axis. This is clearly not in accordance with experience, and it will be evident that this diagram exaggerates the scatter at high stress levels and, *per contra*, minimises the scatter at low stress levels. In a practical case, σ would be a function of the

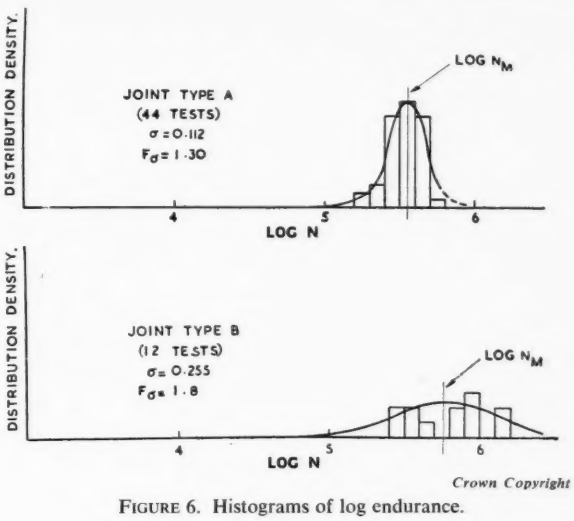

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FIGURE 6. Histograms of log endurance.

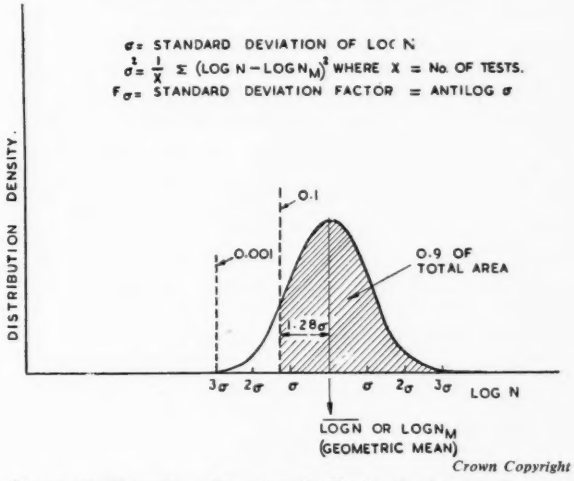
σ = STANDARD DEVIATION OF LOG N
σ² = 1/X Σ (LOG N − LOG N_M)² WHERE X = No. OF TESTS.
Fσ = STANDARD DEVIATION FACTOR = ANTILOG σ
DISTRIBUTION DENSITY.
0·1
0·001
0·9 OF TOTAL AREA
1·28σ
3σ 2σ σ
σ 2σ 3σ
LOG N
LOGN OR LOGN_M
(GEOMETRIC MEAN)

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FIGURE 7. Normal, or Gaussian distribution for log *N*. Constant mean and alternating stress.

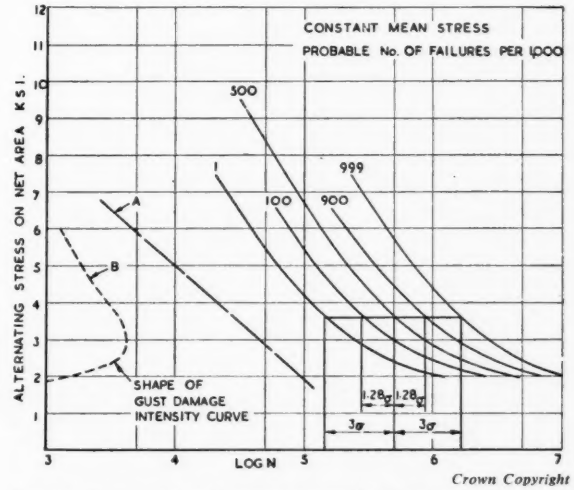

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FIGURE 8. $P-S-\log N$ curves assuming $F_\sigma = 1{\cdot}5$ for all stress levels.

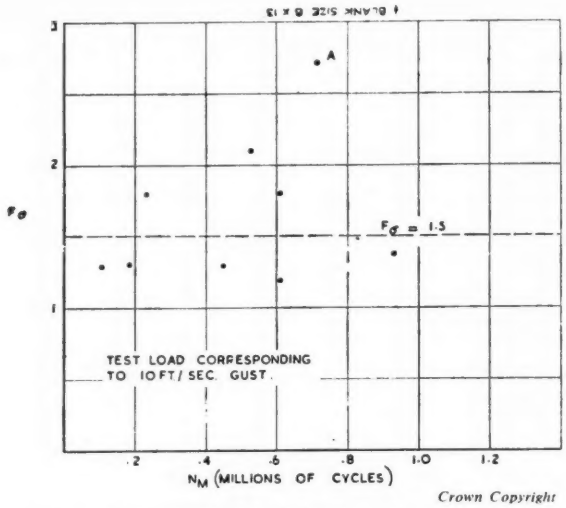

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FIGURE 9. F_σ = standard deviation factor for endurance.

stress level. To put this diagram in perspective, a hypothetical gust load spectrum *A* has been drawn and the shape of the gust damage intensity curve to be expected has been indicated by a broken curve *B*. Relative damage intensity at a given stress level is represented by the distance of this curve from the stress axis. Thus, in damage computation, we are concerned, in the main, with stress alternations varying between 2,000 and 7,000 lb./in.^{2}, and the maximum damage intensity corresponds with a mean endurance in the region of 10^6 cycles. The variation in F_σ over this range may be considerable, but to obtain reliable data on this variation would, of course, involve an enormous number of tests. With present information, all we can do is to determine a representative value of F_σ for the endurance range corresponding to maximum damage intensity and make some rational assumption as to the variation of F_σ with mean endurance.

Figure 9 shows values of F_σ plotted against N_M for a number of test batches on a variety of joint specimens. The wide scatter indicated by the point *A* was attributable to unusually wide variation in the plastic range of the material. The test level used in every case was that corresponding to a 10 ft./sec. gust increment, and is therefore at a loading fairly close to the highest rate of damage from gusts. The value $F_\sigma = 1.5$ shown by the broken line seems reasonably representative of these joint tests and by no means at variance with values found for the tests on Mustang wings. For higher loads, where the mean endurance is of the order 10^4 to 10^5 cycles, lower values of F_σ are to be expected.

Scatter in gust loading, as distinct from scatter in endurance, must be taken into account. Variations in cruising speed, all-up-weight, operational altitude, and percentage of time at low altitude should all be covered by an appropriate safety factor. The computation of damage will not be discussed here, having been well covered recently by Lundberg and by Eggwertz[6].

Let it now be supposed that the designer has computed the safe life for a chosen U.D.S. If the extra material required to raise the estimated life to the design figure is found to be excessive, the designer must either make provision for the replacement of spars (using a "fatigue meter" to record load fluctuations in service) or seek more advanced forms of construction. More use might be made of interference fit pins and bushes at critical bolt holes, and of local reinforcement with the aid of modern adhesives.

By the time the aircraft is ready for production, sufficient laboratory testing should have been done to check the actual spar endurances against the assumed values and to introduce detail improvements and local strengthening if found necessary. Finally, a "flight cycle" test of the complete aircraft as done for the Comet and the Britannia, will ensure that no structural fatigue weaknesses have been overlooked, and indicate which regions require regular inspection for cracks, as well as allowing more detailed investigation of local stresses, and of any stress redistribution as a result of high loads.

If the designer pays sufficient attention to choice of material, to the smooth flow of stress, particularly at joints, and makes full use of the interference and clamping techniques, I can see no reason why the safe life of wings should not reach 30,000 flying hours for operational altitudes above 20,000 feet with very little weight penalty.

NOTE

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TECHNICAL NOTES

Contributions to this Section of the JOURNAL *will be eligible for Journal Premium Awards and will normally be published within two months of being received.*

Note on the Motion Inside a Region of Recirculation (Cavity Flow)

by
H. B. SQUIRE
(*Imperial College*)

IT IS SHOWN that the flow in a region of recirculation may be divided into a core, in which the vorticity may be constant, and a boundary layer surrounding the core. An approximate solution is given for the flow inside a circular cylinder with partly fixed and partly moving walls.

1. INTRODUCTION

Flow patterns which include regions of recirculation occur frequently, for example, behind bluff bodies, in sharp bends, and in sudden expansions in ducts. Little is known about this type of flow, which will be referred to, for brevity, as ' cavity ' flow. It used to be thought that the velocities in the ' cavity ' were small compared with the stream velocity, but it is now known that the maximum velocity in the cavity may be about 30 per cent. of the stream velocity. This implies that the motion within the cavity cannot be neglected. Crocco and Lees[1] have tried to solve the problem of flow behind the base of a projectile by the use of the boundary layer momentum equation with boundary layer profiles containing reversed flow regions. It seems unlikely that this method can be developed to be of general use. A more hopeful approach seems to be to divide the cavity into a ' core ' with a boundary layer outside it (Figs. 1 and 2). The motion in the cavity is maintained by the shear stress of the outer flow acting on the streamline boundary of the cavity. Of course, in many problems of this type the core may be of small extent compared with the extent of the boundary layers, but the concept of cavity flow as consisting of a central core surrounded by a boundary layer may still be useful.

The ideas discussed in the present note* are based on the work of Batchelor[2] on free convection. No problem of cavity flow with outer stream has been solved up to the present, but the type of motion which may occur is indicated by a solution for the flow inside a circular cylinder with partly fixed and partly moving walls, which is given below.

Slow motion problems of cavity flow have been investigated theoretically by Mabey[3]. He also made experiments on the flow inside a cylinder with partly fixed and partly moving walls.

2. FLOW IN THE CORE

The motion is taken to be steady and two-dimensional in the x, y plane.

The equation for the vorticity ζ is

$$\frac{D\zeta}{Dt}=\nu\nabla^2\zeta \qquad . \quad . \quad . \quad (1)$$

in the usual notation. The core is defined to be the region in which viscosity effects are small, although clearly viscosity is responsible for the development of the motion in the core. Thus the right hand side of (1) may be neglected within the core and the solution is then

$$\zeta=f(\psi), \qquad . \quad . \quad . \quad . \quad (2)$$

where ψ is the stream function of the motion. Equation (2) states that in two-dimensional flow the vorticity is constant along streamlines, if viscosity effects are absent: this is a well-known result. An equivalent statement is that the total pressure is constant along streamlines within the core. This latter statement will also apply to motion in a three-dimensional core, for which the vorticity will not be constant along streamlines.

It has been shown[2] that the vorticity will probably be constant in the core in some two-dimensional free convection problems and this result may also apply to some two-

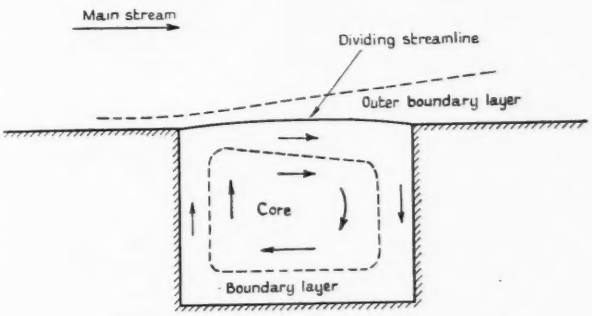

FIGURE 1.

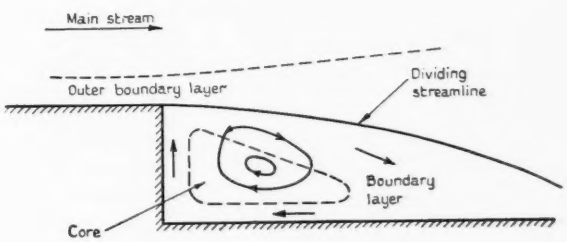

FIGURE 2.

*A paper by Dr. Batchelor on the present subject will be published in the first issue of the *Journal of Fluid Mechanics*.

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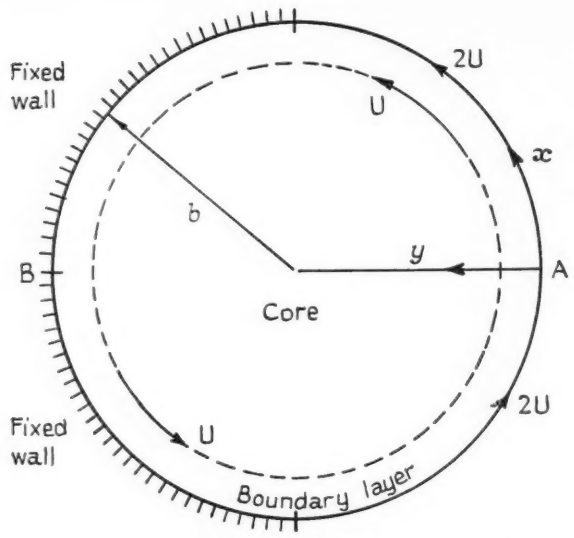

FIGURE 3. Motion inside a cylinder with partly fixed and partly moving walls.

dimensional cavity flow problems. The argument for this can be stated simply in the form that the vorticity will tend to a constant in the core, owing to the residual action of viscosity, since viscosity tends to destroy vorticity gradients as far as possible (cf. equation (1)).

This provisional conclusion that the vorticity is constant in the core may not be applicable to the important practical cases of cavity flow, because the flow in the mixing region of the inner and the outer streams will generally be turbulent. Due to the high rate of mixing here, some of the streamlines of the core motion may cross into and out of this mixing region (Fig. 2). In this case each streamline will have a constant vorticity within the core, but the vorticity may not be uniform throughout the core.

3. FLOW IN THE BOUNDARY LAYER OF THE CAVITY

As usual in boundary layer theory we measure x along the edge of the cavity, which may consist entirely of walls (Fig. 3) or partly of walls and partly of a streamline separating the cavity flow from the outer stream (Figs. 1 and 2). We suppose for the present that the boundary layer of the cavity flow is a thin skin round the core; the validity of this hypothesis can be examined when solutions have been obtained. Measure y normal to the cavity boundary inwards towards the core. Let u and v be the velocity components in the boundary layer in the x and y directions respectively and U be the velocity along the inner edge of the boundary layer and outer edge of the core. Then for incompressible flow the boundary layer equation takes the usual form

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=U\frac{dU}{dx}+\nu\frac{\partial^2 u}{\partial y^2} \quad . \quad . \quad (3)$$

It seems likely that the complexity of the boundary layer flow, which is periodic in character, will make the construction of solutions of this equation difficult. It is therefore proposed to simplify it by introducing the Oseen approximation, which reduces it to the simpler linear equation

$$U\frac{\partial u}{\partial x}=U\frac{dU}{dx}+\nu\frac{\partial^2 u}{\partial y^2}. \quad . \quad . \quad (4)$$

In general U will be a function of x and the solution of (3) or (4) will have to be joined up to the (unknown) boundary layer solution for the outer stream. If we put $X=\int\frac{dx}{U}$ equation (4) becomes

$$\frac{\partial}{\partial X}(u-U)=\nu\frac{\partial^2}{\partial y^2}(u-U)$$

which is equivalent to the equation of heat conduction.

4. FLOW INSIDE A CYLINDER WITH PARTLY FIXED AND PARTLY MOVING WALLS

The simplest problem in cavity flow is the motion inside a circular cylinder of radius b for which half the circumference is fixed and the other half is moving tangentially with velocity $2U$ (Fig. 3). If the boundary layer is thin the core nearly fills the cylinder. Constant vorticity in the core implies that the fluid in the core has a solid body rotation. The velocity at the edge of the core is constant and is taken to be equal to U, one half of the wall velocity; it will be verified below that this is correct. The equation for the velocity in the boundary layer (4) becomes

$$U\frac{\partial u}{\partial x}=\nu\frac{\partial^2 u}{\partial y^2}, \quad . \quad . \quad . \quad (5)$$

with the boundary conditions:—

$$\left.\begin{aligned} u&=2U \quad \text{for} \quad -\pi/2<x/b<\pi/2\\ u&=0 \quad \text{for} \quad \pi/2<x/b<3\pi/2\end{aligned}\right\} \quad . \quad (6)$$

$$u\longrightarrow U \quad \text{for} \quad y\longrightarrow\infty \quad . \quad . \quad (7)$$

The solution of (5) having the correct periodic character is constructed from the type solution

$$u=\exp\left[ipx\pm\left(\frac{ipU}{\nu}\right)^{1/2}y\right],$$

where p is a constant, and it is found that the solution is of the form

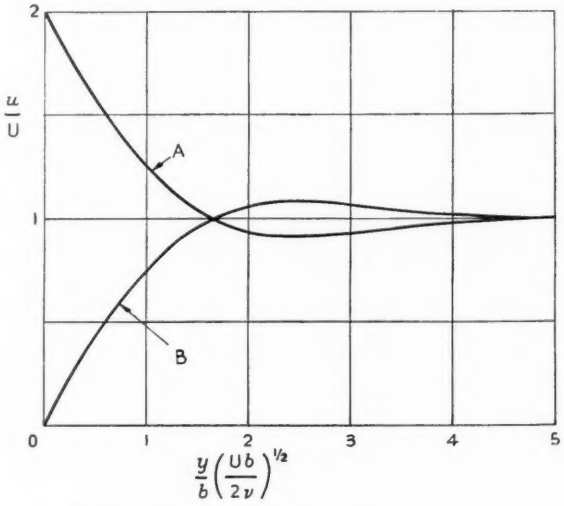

FIGURE 4. Velocity distribution in boundary layer.

$$\frac{u-U}{U} = \sum_{1}^{\infty} a_n \exp\left(-\frac{kn^{1/2}y}{b}\right)\cos\left(\frac{nx-kn^{1/2}y}{b}\right) \quad (8)$$

where $k=[Ub/(2\nu)]^{\frac{1}{2}}$ and the a_n are constants. This form satisfies the boundary condition (7). At the wall equation (8) gives

$$\frac{u-U}{U} = \sum_{1}^{\infty} a_n \cos\left(\frac{nx}{b}\right).$$

To satisfy the boundary condition (6), this series must be the Fourier series expansion of the function which is equal to $+1$ in the range $-\pi/2 < x/b < \pi/2$ and equal to -1 in the range $\pi/2 < x/b < 3\pi/2$ and hence

$$a_{2n}=0, \qquad \sum_{1}^{\infty} a_{2n+1} = \frac{4(-)^n}{\pi(2n+1)}.$$

The velocity distribution in the boundary layer at the stations A $(x=0)$ and B $(x=\pi b)$ is shown in Fig. 4, and is oscillatory at the outer edge. The boundary layer thickness is found from Fig. 4 to be approximately equal to $7(\nu b/U)^{\frac{1}{2}}$.

We now verify that the velocity at the edge of the core has been correctly taken to be U. This is so because the solution obtained gives zero torque applied by the walls to the fluid in the cylinder, which is shown by checking that the velocity gradients at two points at opposite ends of a diameter are equal and opposite; Fig. 4 gives an example of this.

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Stability Criteria for Linear Equations with Time-Varying Coefficients

by

P. E. W. GRENSTED, M.A.

(Department of Engineering, Cambridge University)

RECENT interest has been shown in stability problems in which the parameters in the relevant characteristic equations are not constant. For instance, the coefficients in the characteristic equation for the stability of flutter of an aeroplane's wings are functions of the speed of the aircraft. When the aircraft is accelerating or decelerating it is therefore necessary to consider whether the resulting variation of the coefficients is sufficiently rapid to invalidate a calculation of stability which is based on the assumption that the coefficients are constant. Similar stability problems arise in connection with guided missiles.

It is known from work on the second order linear equation with time-varying coefficients that a " criterion of stability " analogous to Routh's criterion depends not only on the instantaneous values of the coefficients but also, to some extent, on their derivatives. This result is well demonstrated by a theorem due to Sonin described in the Appendix. If the coefficients are varying sufficiently slowly this latter dependence may be regarded as a second-order effect. Indeed it is obvious that where the coefficients are varying very slowly indeed, Routh's criterion applied to the instantaneous values of the coefficients will give satisfactory and meaningful results.

This note attempts to find the conditions that the rates of change of the coefficients must satisfy in order that Routh's criterion is adequate when applied to the instantaneous values of the coefficients alone.

Secondly, a modified Routh's criterion is derived which gives an indication of the effect that the rate of change of coefficients has on the stability of the true solution. The method used is applicable to equations of any order, and the results given here are for equations of the second, third and fourth order.

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The method used is by no means rigorous and is put forward tentatively as a possible approach to the problem.

1. METHOD

The modified form of Routh's criterion to be derived is based on the assumption that, to a first order, the required criterion will depend only on the instantaneous values of the coefficients and their first derivatives.

Now for any order linear equation it is possible to transform to a new time variable, τ (with $d\tau/dt > 0$), such that at any specific instant of true time, t, the derivatives with respect to τ of the coefficients in the new equation are all zero. We also have the fundamental fact that if a system is stable in the new time scale, τ, it is also stable in the true time scale, t, provided that $d\tau/dt$ is positive.

Finally, since we assume that the stability criterion only depends on the coefficients and their first derivatives, the criterion becomes simply Routh's criterion applied to the instantaneous values of the coefficients in the new equation, for their derivatives with respect to τ are all zero.

The method of deriving the new equation is now described with reference to a second order equation.

2. THE SECOND ORDER EQUATION

Consider the equation

$$a\ddot{x} + b\dot{x} + cx = 0, \qquad . \quad . \quad (1)$$

where a and b are functions of time, and c is constant. Dots denote differentiation with respect to t.

Let τ be a function of t, then a new equation in the time scale τ may be derived from equation (1). If dashes denote differentiation with respect to τ, we have

$$\dot{x} = \dot{\tau}x'; \qquad \ddot{x} = \dot{\tau}^2 x'' + \ddot{\tau}x'. \quad . \quad (2)$$

Hence equation (1) becomes

$$a\dot{\tau}^2x'' + (b\dot{\tau} + a\ddot{\tau})\,x' + cx = 0,$$

or

$$Ax'' + Bx' + Cx = 0,$$

where

$$A = a\dot{\tau}^2; \qquad B = b\dot{\tau} + a\ddot{\tau}; \qquad C = c. \qquad . \qquad (3)$$

It is now required to choose τ so that the new coefficients, A, B and C, have their first derivatives with respect to τ equal to zero at a particular instant of time. This is done as follows.

Measuring true time from the particular instant in which we are interested, let

$$\dot{\tau} = 1 + v_1 t + \tfrac{1}{2}v_2 t^2 + \ldots,$$
$$a = a_0 + a_1 t + \tfrac{1}{2}a_2 t^2 + \ldots, \qquad . \qquad . \qquad (4)$$
$$b = b_0 + b_1 t + \tfrac{1}{2}b_2 t^2 + \ldots,$$

where $v_1, v_2, \ldots a_0, a_1, a_2, \ldots b_0, b_1, b_2, \ldots$ are constant.

Then from equations (3) and (4)

$$A = a_0 + (2v_1 a_0 + a_1)\,t + \ldots \qquad . \qquad (5)$$

$$B = b_0 + a_0 v_1 + (c_0 v_1 + b_1 + a_0 v_2 + a_1 v_1)\,t + \ldots \qquad (6)$$

If we impose the condition that $A' = B' = 0$ at $t = 0$ (*i.e.* that $\dot{A} = \dot{B} = 0$, since $\dot{\tau} = 1$ at $t = 0$) we must have the coefficients of t in equations (5) and (6) equal to zero.

Thus, from equation (5), $v_1 = -\tfrac{1}{2}a_1/a_0$, and so the values of A and B at $t = 0$ become

$$A = a_0,$$

and

$$B = b_0 - \tfrac{1}{2}a_1.$$

Finally, since there is no restriction on the instant from which t is measured, we may write more generally

$$A = a; \qquad B = b - \tfrac{1}{2}\dot{a}; \qquad C = c.$$

3. LIST OF DERIVED EQUATIONS

A list of derived equations for the second, third and fourth order is now given, and can be used as follows.

(*i*) Routh's criterion may be applied to the original equation provided that in the expressions for A, B, C, and so on, the terms involving derivatives of coefficients are small compared with the first term in each expression.

(*ii*) Routh's criterion applied to the derived equation gives an indication of the effect of the rates of change of the coefficients on the stability of the solution of the original equation.

3.1. *First Order*

Original equation: $a\dot{x} + bx = 0,$

Derived equation: $Ax' + Bx = 0,$

where $A = a; \qquad B = b.$

3.2*a*. *Second Order*

Original equation: $a\ddot{x} + b\dot{x} + cx = 0, \qquad c = \text{constant}.$

Derived equation: $Ax'' + Bx' + Cx = 0,$

where $A = a; \qquad B = b - \tfrac{1}{2}\dot{a}; \qquad C = c.$

3.2*b*. *Second Order*

Original equation: $a\ddot{x} + b\dot{x} + cx = 0, \qquad a = \text{constant}.$

Derived equation: $Ax'' + Bx' + Cx = 0,$

where $A = a; \qquad B = b + \tfrac{1}{2}a\dfrac{\dot{c}}{c}; \qquad C = c.$

3.3*a*. *Third Order*

Original equation: $a\dddot{x} + b\ddot{x} + c\dot{x} + dx = 0, \qquad d = \text{constant}.$

Derived equation:

$$Ax''' + Bx'' + Cx' + Dx = 0,$$

where $A = a; \qquad B = b - \dot{a};$

$$C = c - \frac{1}{3}\dot{b} - \frac{1}{9}b\frac{\dot{a}}{a} - \frac{2}{9}\frac{\dot{a}^2}{a}; \qquad D = d.$$

3.3*b*. *Third Order*

Original equation: $a\dddot{x} + b\ddot{x} + c\dot{x} + dx = 0, \qquad a = \text{constant}.$

Derived equation: $Ax''' + Bx'' + Cx' + Dx = 0,$

where $A = a; \qquad B = b + a\dfrac{\dot{d}}{d};$

$$C = c - \frac{1}{3}\dot{b} + \frac{4}{9}b\frac{\dot{d}}{d} + \frac{2}{9}a\frac{\dot{d}^2}{d^2}; \qquad D = d.$$

3.4*a*. *Fourth Order*

Original equation: $a\ddddot{x} + b\dddot{x} + c\ddot{x} + d\dot{x} + ex = 0, \qquad e = \text{constant}.$

Derived equation: $Ax'''' + Bx''' + Cx'' + Dx' + Ex = 0,$

where $A = a; \qquad B = b - \dfrac{3}{2}\dot{a};$

$$C = c - \frac{2}{3}\dot{b} - \frac{1}{4}\frac{b}{a}\dot{a};$$

$$D = d - \frac{1}{4}\dot{c} - \frac{1}{24}\frac{b}{a}\dot{b} + \frac{1}{24}\frac{b^2}{a^2}\dot{a} - \frac{1}{8}\frac{c}{a}\dot{a};$$

$$E = e.$$

Second order correction terms, *e.g.* $\dot{a}^2$, $\dot{a}\dot{b}$, and so on, have been neglected.

3.4*b*. *Fourth Order*

Original equation: $a\ddddot{x} + b\dddot{x} + c\ddot{x} + d\dot{x} + ex = 0, \qquad a = \text{constant}.$

Derived equation: $Ax'''' + Bx''' + Cx'' + Dx' + Ex = 0,$

where $A = a; \qquad B = b + \dfrac{3}{2}a\dfrac{\dot{e}}{e};$

$$C = c - \frac{2}{3}\dot{b} + \frac{11}{12}b\frac{\dot{e}}{e};$$

$$D = d - \frac{1}{4}\dot{c} - \frac{1}{24}\frac{b}{a}\dot{b} + \frac{3}{8}c\frac{\dot{e}}{e}; \qquad E = e.$$

Second order correction terms have been neglected.

4. EXAMPLES

4.1. *The Second Order Equation*

The criterion obtained using the derived equation for the second order (Section 3.2) agrees with Sonin's Theorem which is an exact result.

An alternative interesting time transformation for the equation

$$a\ddot{x} + b\dot{x} + cx = 0, \qquad a = \text{constant}, \qquad ac > 0,$$

is $$\dot{\tau} = +\sqrt{(c/a)}.$$

This leads to the following transformed equation:

$$x'' + \frac{1}{+\sqrt{(ca)}}\left(b + \frac{1}{2}\,a\,\frac{\dot{c}}{c}\right)x' + x = 0.$$

The damping coefficient is now the only one dependent on τ. The sign of this term, and hence the stability of x, depends only on the sign of $\left(b + \frac{1}{2}\,a\,\frac{\dot{c}}{c}\right)$.

This result agrees with Sonin's Theorem and Section 3.2*b*.

4.2. *The Third Order Equation*

Examples of the use of the derived equation for the third order (Section 3.3) are now given, and the accuracy of the method illustrated.

(*i*) *Reduction to Second Order.* In Section 3.3*b* put $a = 0$ and $b =$ constant, thus reducing to the second order case (Section 3.2*b*).

Then $B = b; \qquad C = c + \frac{4}{9}\,b\,\frac{\dot{d}}{d}; \qquad D = d.$

Or, using the notation of the second order case (*i.e.* replacing B and b by A and a, C and c by B and b, and so on) the relations become

$$A = a; \qquad B = b + \frac{4}{9}\,a\,\frac{\dot{c}}{c}; \qquad C = c.$$

Comparison with the relations given in Section 3.2*b* shows a small discrepancy in the numerical coefficient of the correction term in the expression for B (4/9 c.f. 1/2).

(*ii*) *Homogeneous Equation.* Application of Section 3.3*b* to the homogeneous equation

$$\alpha t^3\dddot{x} + \beta t^2\ddot{x} + \gamma t\dot{x} + \delta x = 0,$$

where α, β, γ and δ are constant, yields

$$A = \alpha t^3; \qquad B = (\beta - 3\alpha)\,t^2;$$

$$C = (\gamma - \beta - 2\alpha)\,t; \qquad D = \delta.$$

Thus Routh's criterion of stability becomes that the above expressions for A, B, C and D must have the same sign, and that

$$\alpha\delta < (\beta - 3\alpha)(\gamma - \beta - 2\alpha).$$

This may be verified to be correct. It can be shown that the method of deriving A, B, and so on, will always give the correct result for homogeneous equations of any order.

(*iii*) *Example with Known Solution.* Consider the following equation, in which $\alpha\,(>0)$ is an arbitrary function of time:

$$(\alpha+1)\dddot{x} + (\alpha+1-\dot{\alpha})\ddot{x} + \alpha(\alpha+1)\dot{x} + (\alpha^2+\alpha+\dot{\alpha})x = 0. \qquad . \quad . \quad . \quad (7)$$

Now it may be verified that there are two linearly independent solutions of equation (7) satisfying respectively the equations

$$\dot{x} + x = 0, \qquad . \quad . \quad . \quad (8)$$

$$\ddot{x} + \alpha x = 0. \qquad . \quad . \quad . \quad (9)$$

Equation (8) represents a stable mode. Equation (9) represents a stable mode if, and only if, $\dot{\alpha} > 0$, by Sonin's Theorem. (If $\dot{\alpha} = 0$ there is neutral stability.)

Applying Routh's criterion to the instantaneous values of the coefficients in equation (7) gives the following inequality for stability:

$$(\alpha+1)(\alpha^2+\alpha+\dot{\alpha}) < (\alpha+1-\dot{\alpha})\,\alpha(\alpha+1),$$

$$i.e. \quad \dot{\alpha} < 0.$$

This is the wrong result.

Now apply Routh's criterion to the transformed equation. Dividing equation (7) by $\alpha+1$, and using Section 3.3*b*, we find

$$A = 1; \qquad B = 1 + \frac{\dot{\alpha}}{\alpha(\alpha+1)};$$

$$C = \alpha + \frac{4}{9}\,\frac{\dot{\alpha}}{\alpha}; \qquad D = \alpha + \frac{\dot{\alpha}}{1+\alpha};$$

where terms involving $\dot{\alpha}^2$ and $\ddot{\alpha}$ have been ignored in comparison with $\dot{\alpha}$, α and 1. Applying Routh's criterion, $AD < BC$, yields (again neglecting second order terms) stability if

$$\dot{\alpha} > 0.$$

This is the correct result.

5. CONCLUSIONS

It is left to the end to explain the term stability as applied in this note. It has been assumed throughout that the variation of coefficients is a second order effect, and so the solution may be regarded as a linear combination of exponential terms and damped oscillatory terms in which the decay time constants are varying. "Stability" implies that all these time constants are positive.

The list of derived equations in Section 3 shows how the rates of change of coefficients can modify the stability criterion, and hence shows when it is justifiable to neglect them.

Finally, it must be emphasised that the underlying assumption throughout this note has been that only the first derivatives of the coefficients affect the stability criteria. While this is true for second order equations, it is not entirely true for higher orders; the method given must be regarded as only a first order improvement on the "quasi-linear" stability obtained by applying Routh's criterion to the instantaneous values of coefficients in the original equation.

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APPENDIX: Sonin's Theorem

Attention has been drawn by Professor Collar to an extension by Pólya of a theorem due to Sonin. This theorem is conveniently stated as follows:

If x is the solution of

$$\ddot{x} + b\dot{x} + cx = 0, \qquad . \quad . \quad . \quad (1)$$

where b and c are functions of t, then, in a given range of t, successive maxima, if any, of x^2 increase if $(2bc+\dot{c})<0$ and decrease if $(2bc+\dot{c})>0$ in that range.

The theorem is proved by considering the energy function

$$f=x^2+(\dot{x})^2/c. \quad . \quad . \quad . \quad (2)$$

Differentiating equation (2) with respect to t, and using equation (1), yields

$$\dot{f}=-(\dot{x})^2(2bc+\dot{c})/c^2. \quad . \quad . \quad (3)$$

Maxima of x^2 occur when $\dot{x}=0$, hence from equation (2) successive maxima increase with f. Hence from equation (3) successive maxima increase if $(2bc+\dot{c})<0$ and decrease if $(2bc+\dot{c})>0$.

From this theorem it is apparent that the solution, x, of equation (1) may be regarded as stable if $(b+\frac{1}{2}\dot{c}/c)>0$ and $c>0$. That the latter condition is necessary is seen by an inspection of equation (1) when $\dot{x}=0$. This criterion of stability depends on the rate of change of the coefficient c. The corresponding Routh criterion of stability for constant coefficients is $b>0$ and $c>0$.

The Size of Aerofoil Models for Quantitative Hydraulic Analogy Research

by

R. A. A. BRYANT, A.S.T.C., A.M.I.E.Aust., Companion R.Ae.S.

(The New South Wales University of Technology)

IN A RECENT ARTICLE[1] Lundberg has made reference to use of the " Hydraulic Analogy " for quantitative investigation of gas dynamics phenomena. This is quite feasible provided that the basic analogy and its limitations are properly understood. In fact, considerable progress has already been made and it has been proved possible to utilise the analogy for both supersonic and transonic research[2].

A study of the mathematical analogy[3] indicates that the strongest physical analogy between a two-dimensional (inviscid) gas flow and a three-dimensional (viscous) water flow exists for the transonic case when the water depth is approximately one quarter inch and the model is towed. Only thin profiles with small incidence can be sensibly investigated. Under such conditions the analogous water flow may be considered as a distorted dissimilar model of a corresponding prototype gas flow[4]. To transfer data to prototype conditions some form[3,4,5] of Kármán's Transonic Similarity Law may be used with additional considerations taking into account the influence of the boundary layer along the sides of the model.

The boundary layer, as well as producing some small discrepancies near the boundaries not compatible with gas flow, gives an " effective " model profile which is not an affine transformation of the physical profile tested. Nevertheless, simple first order corrections based on the boundary layer displacement thickness[4] can be made which partly overcome the difficulty. Over the rear portion of aerofoils the discrepancy between the " effective " and required " physical " profiles cannot be overcome unless some modification is made to the profile of the model being towed. As the towing velocities are low, the boundary layer is laminar and little separation occurs at the trailing edge: this permits modification of the model from symmetry considerations.

As an example, consider a double wedge profile, shown in Fig. 1(*a*).

NOTATION

- t profile thickness
- l chord length
- M_{01} free stream Mach number in analogous water flow (equal to Froude number)
- C_w celerity of small amplitude surge in water (analogous to velocity of sound)
- δ_1^* displacement thickness of boundary layer at distance $l/2$ from leading edge
- δ_2^* displacement thickness at trailing edge of model (modified profile)
- ν kinematic viscosity.

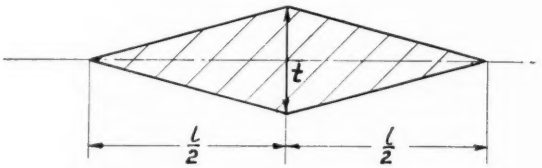

FIGURE 1(*a*). Profile required to be investigated.

For all cases of practical interest, δ_1^* and δ_2^* may be computed as for a flat plate due to the profile being thin. Neglecting the curvature of the displacement boundary layer, δ_1^* and δ_2^* may be used to define an effective profile which is an affine transformation of the required profile. This effective profile is obtained simply by shortening the length of the rear portion as shown in Fig. 1(*b*).

The length x is obtained from the equality:

$$\frac{t+2\delta_1^*}{l}=\frac{2\delta_2^*}{l-2x} \quad . \quad . \quad . \quad (1)$$

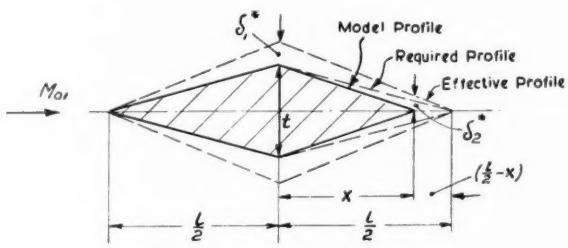

FIGURE 1(*b*). Modified profile.

Received 9th January 1956.

where $\delta_1^* = 1{\cdot}73\sqrt{\left(\frac{\nu}{M_{01}C_w}\right)}\sqrt{\left(\frac{l}{2}\right)}$

and $\delta_2^* = 1{\cdot}73\sqrt{\left(\frac{\nu}{M_{01}C_w}\right)}\sqrt{\left(\frac{l}{2}+x\right)}$

Solution of equation (1) gives:

$$x = \frac{l}{2} + \frac{A^2}{8B^2} - \frac{1}{2}\frac{A}{B}\sqrt{\left(\frac{A^2}{16B^2}+l\right)} \quad . \quad (2)$$

where $A = 3{\cdot}46\sqrt{\left(\frac{\nu}{M_{01}C_w}\right)}$,

and $B = \dfrac{t + A\sqrt{\left(\frac{l}{2}\right)}}{l}$.

To obtain first order values of x, equation (2) may be simplified by considering the order of the variables A and B.

Thus $O(A) = 0{\cdot}01\ ft^{\frac{1}{2}}$

$$O(B) = \frac{t}{l}$$

Consequently $O\left(\frac{A^2}{8B^2}\right) = 0,$

$$O\left(\frac{A}{B}\sqrt{\left(\frac{A^2}{16B^2}\right)}\right) = 0$$

and $$x = \frac{l}{2} - \frac{A}{2B}\sqrt{l} \quad \text{to first order} \quad (3)$$

or $$\frac{x}{l/2} = 1 - \frac{0{\cdot}01}{t}\sqrt{l} \quad . \quad . \quad (4)$$

Values of the ratio $x/(l/2)$ for thickness/chord ratios ranging from 5 per cent. to 30 per cent. and chord lengths 3 in., 6 in., 12 in. and 24 in. are shown in Fig. 2.

It will be seen that the magnitude of the modification is reduced with large chord lengths and increasing thickness ratios. For the thinner profiles the necessity of using the larger models is obvious.

From a practical point of view the use of a large model has other advantages, the most important probably being that by keeping the lost length $(l/2 - x)$ small the depth distributions at the physical profile and the effective profile may be considered the same.

At the present time it does not appear as if any N.A.C.A. type analogy tank (*see* Ref. 6 and Fig. 24 of Ref. 1) has been constructed which will enable chord lengths of 12 to 24 in. to be used. The use of relatively small models together with the influence of the boundary layer formed along the bottom of the tank, which has a marked deleterious influence on the physical analogy and produces secondary surface disturbances when the water depth is below about one half inch, are no doubt

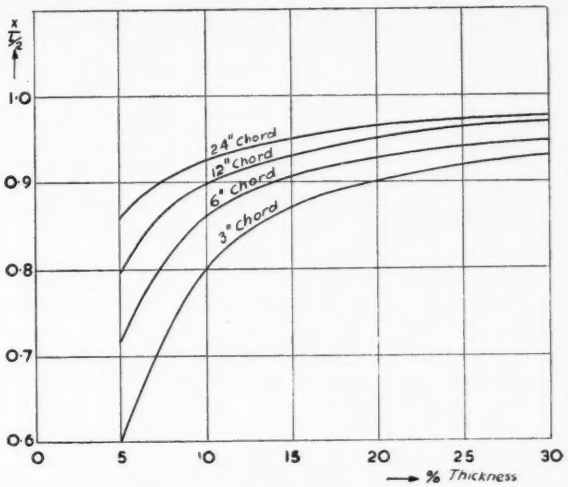

FIGURE 2. Modification of afterbody.

additional factors which have led some workers to the conclusion that only qualitative information can be obtained[7]. Within the transonic where the existence of shocks does not break down the basic analogy to the same extent as in the supersonic, the factors already mentioned are of great importance and still make it impossible to obtain quantitative results from N.A.C.A. type tanks.

The results of the M.I.T. supersonic experiments[2] show that a channel which utilises variable bed slope to produce supercritical flow has distinct advantages and allows large models to be used; for transonic studies the towed model analogy is recommended.

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A New Method for the Numerical Evaluation of Determinants

IN the November 1955 issue of the JOURNAL there is a Note, " A New Method for the Numerical Evaluation of Determinants." I would point out that this method is not new, but is given in " The Theory of Determinants, Matrices and Invariants " by Turnbull (published by Blackie) at page 340, paragraph 7, under the heading " Dodgson's Method of evaluating a determinant by condensation."

The Method given is identical to that of your author. The book quoted is a well established standard treatise on this subject.

A. T. F. NICE, M.A.(Cantab.),
(Lecturer in Mathematics, Kingston-on-Thames Technical College)

I AM very interested to learn that the Rev. C. L. Dodgson, *alias* Lewis Carroll, had already discovered this method. I have traced the original and found it in that famous " Elementary Treatise on Determinants," which might have been dedicated to Queen Victoria, as she had signified that his next book after " Through the Looking-Glass " might be so inscribed. Dodgson first published the method in the *Proceedings of the Royal Society*, 1866, and suggested the name " condensation " be used for the technique. He did not give a general proof of its validity.

It is perhaps useful that the method should be brought to light again, as it seems to have advantages for automatic digital computation, which did not exist when it was first proposed, and it seems to have been forgotten. As to the possibility of discovering a really new method in a well-trodden field, one is reminded of the Red Queen's remark that it takes all the running one can do to stay in the same place.

R. H. MACMILLAN,
(Engineering Laboratory, University of Cambridge)

Traian Vuia—A Little-Known Pioneer

by

BERNARD ORNA

MARCH 18th is the 50th anniversary of a free flight of some 40 ft. made at Montesson, near Paris, by Traian Vuia credited by *L'Aérophile* (September 1906) with being " the first person in France to have really attempted, with a machine able to carry a man, the direct take-off of an aeroplane having a wheeled undercarriage."

Vuia, a Rumanian, submitted a paper to the Academy of Sciences in February 1903 which included a description of what he called an " aéroplane-automobile " which was a light weight monoplane with wheels and an engine driving a single tractor propeller; it was to be controlled by a rudder and by altering the incidence of the wing.

Towards the end of 1905 his first aeroplane was completed. It consisted of a triangular tubular steel frame on four wheels and pivoting wings with a span of 21 ft. mounted on top of the frame. The 25 h.p. engine, designed by Vuia, was a " steam unit, modified to take carbonic acid carried in liquid form and then vaporised—with burners fuelled by petrol " (*La Nature* 1906).

Further flights were made by Vuia that summer. Hampered by lack of money in pursuing his work, Vuia's achievement was over-shadowed by the successes, first of Santos-Dumont, then of Archdéacon, Blériot and others which soon followed. His aeroplane has survived and is in the possession of the Aeronautical Museum in Paris. Vuia died in Rumania in 1950 shortly after his return to that country after many years in France, one of the little-known but worthy pioneers of flight.

Graduates' and Students' Section

This page of the Journal is written by members of the Committee of the Graduates' and Students' Section. Each month it covers matters of interest and importance to Graduates and Students and previews lectures and visits.

Questionnaire on the Section's Activities

Towards the end of 1955 a questionnaire was circulated to all Graduate and Student members of the Society. It was hoped that the answers to the questions therein would help the Committee to formulate their plans for future activities of the Section. Just under 100 completed questionnaires were returned. This of course represents only a very small proportion, but doubtless a statistical sample of the keener elements of the total graduate and student membership, and to those members who did take the trouble to reply the Committee would like to take this opportunity of expressing their thanks.

It is of particular note that the great majority of the replies were received from the employees of firms or organisations in the London area, or its immediate vicinity. The reason obviously stems from the centralisation of the Section's activities in this area, which at present is an unavoidable state of affairs. However, interest in the Section's activities is not only confined to the London area as is shown by replies from widely scattered points throughout the British Isles.

An analysis of the answers received has revealed a number of interesting facts, and although it was found that the majority of replies were in general satisfied with the present arrangements for lectures and visits it was noteworthy that in reply to the question " which evening do you find most convenient for lectures " the most popular choice was Friday. Up to now this night has not been utilised for lectures but we hope to arrange some lectures for that evening as a future experiment.

Evening visits, again with Friday as the most popular day, were acceptable to about half those who replied, which would seem to indicate that such activities, particularly during the winter months, are worth continuing. Probably these visits could be aimed at visiting places outside those of direct aeronautical interest, and the recent Wine Cellar visit is a good example.

Saturday visits were very popular and most members felt that such events should occupy the whole day. For these occasions visits to the various Ministry of Supply establishments, the N.P.L. and the major Aircraft Manufacturers were given the most support. Many of these visits would entail a fair amount of travelling, but most members were willing to spend at least ten shillings, and many a pound or more, in order to reach such events. Following the success of the visit to the R.A.E., Bedford, last year, for which the section hired a coach, it will be possible by such a method to keep the travelling costs down, provided that we get the same support in the future.

Since many establishments do not work over the weekend it is necessary to arrange a date during the week if such places are to be visited. Most of the replies indicated that members could not attend in these circumstances, but from our recent experience in this direction it has been found that many employers are in fact sympathetic to requests for leave from their staff who wish to take part in such visits, provided that the subject to be visited has some aeronautical bias. We would therefore recommend that when a mid-week visit is arranged you approach your employers; you may get a pleasant surprise.

A large number of suggestions for future lectures were made, and it was particularly interesting to note that practically every suggestion was different, a fair indication of the difficulties inherent in finding lecture subjects which will have a wide appeal. On one hand many members called for less technical lectures than at present, while others bemoaned the simple nature of our current programmes. However, despite all these facts we shall endeavour to provide future lectures to meet some of your ideas.

In these brief notes not all the questions raised in our questionnaire have been dealt with, particularly with regard to social functions; however part of a future issue of this page will discuss the rest of these subjects. If you still have an unused copy of our questionnaire lying around why not fill it in and return it to the Section Chairman, P. A. Hearne, Tiger House, Beaconsfield Road, Farnham Royal, Bucks.?—P.D.S.

Visits

On the 18th January of this year a visit was made to the Wine Cellar of Messrs. H. Sichel & Son which is situated in the historical Adelphi Arches. This peep into a part of the 18th Century London was remarkable for the contrast between the old buildings and the modern wine bottling and crating machinery, which was demonstrated to the visitors. Mr. Sichel himself acted as guide and finally gave a most amusing and informal talk on the problem of wine growing and bottling, as well as on wine tasting. A practical demonstration of the latter art was arranged in which the visitors took part.

The next visit will be to the Fairey Aviation Company on the 17th March, and this will be followed by visits to the Operational R.A.F. Station, West Malling, on the 7th April, and to a U.S.A.F. base on 19th May. Applications for any, or all, of these visits should be sent to the Hon. Visits Secretary, N. K. Benson, 14 Wakering Road, Barking, Essex.—P.D.S.

Lectures

The next lecture is that to be given by Mr. A. V. Cleaver on the 28th March, his subject being " Artificial Space Satellites." This lecture will take place in the Library at 4 Hamilton Place at 7.30 p.m.

During May the Section will be given a lecture by Sir Frederick Handley Page, Hon. Fellow, which should be of outstanding interest to all Graduates and Students.

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Reviews

SELECTED PAPERS ON ENGINEERING MECHANICS. *A tribute to Theodore von Kármán from Students and Associates of the Aachen period. Edited by G. Gabrielli, F. N. Scheubel, and F. L. Wattendorf. Butterworths Scientific Publications, London, 1955. XII, 186 pp. 50s.*

If Theodore von Kármán had not been born, I would have liked to have invented him. He provides me with a perennial proof of the true philosophical content of the human mind. I use the word philosophy in the same sense as put on it by Bertrand Russell, as the No Man's Land between those things amenable to scientific investigation and those apparently not.

When those who learn something from you write a series of first-class papers out of the sheer delight and gratitude of having been taught by you, then you may safely claim to have arrived. If Theodore von Kármán can ever be said to have arrived. It has always seemed to me that he has either always been there or is going somewhere else, and by the time I have arrived he is on his way to a new arrival platform! For he is an industrious traveller.

Three of von Kármán's tributaries (what else would you call those who add their streams of knowledge to the main stream?) edit this remarkable tribute of ten papers. Each editor contributes a paper. They are discussed in the review following this. My part in the review is to recommend the book to you and pay my own tribute to a man who in his youth, and for so long since, has been too good-looking to be true, and who, in the mature moulding of time, has spread his aura world-wide.

You remember this man after your first meeting—and after—always. What is more astonishing is that he remembers you, though you may not see him again for years and six thousand miles away from the place of the first meeting, for he has travelled Europe and America and Asia and the upper reaches of the Cam to take part in great congresses or give advice to governments and lectures to the learned.

In the First World War he was a lieutenant in the Austrian army. In the Second he was one of the chief advisers on technical matters to the greatest armies of freedom this battered old world has known in its long history. If he carried all the medals and Honorary Fellowship scrolls of learned and not so learned Societies which have been given to him, he would want to be servo-controlled to move about. He is one of the few foreign Fellows of the Royal Society.

In the preface to this tribute the editors recall that von Kármán was appointed Professor of Mechanics at the Technische Hochschule, Aachen in 1912. They write:

" Aachen was the first great challenge which Theodore von Kármán had to face alone. He was well equipped for the task: a crystal clear mind, equally adept at analysis and synthesis; a depth of intuition possessed by very few men; an abundant generosity with which he passed on ideas and suggestions to friends and collaborators; amiability and an aptitude for dealing with his fellow men which earned him many devoted friends."

This preface outlines von Kármán's great achievements in the fields of Applied Mechanics and Scientific research, and the editors so rightly point out that he proved himself to be the outstanding interpreter between the engineer and the mathematician for he spoke the language of both.

Born in 1881 he was trained as an engineer in Budapest. In 1909 he became an assistant professor at the University of Gottingen and three years later became the Director of the Aerodynamics at Aachen. In 1930 he became the Professor of Aeronautics at the Daniel Guggenheim Aeronautical Laboratory at the Californian Institute of Technology. This is not the place nor is there the space to detail all his activities and appointments, but I would like to mention one unexpected one. In 1936 he was appointed consultant to the Metropolitan Waterboard, District of California.

No tribute to von Kármán can ignore the character of the man, for he is quite exceptional in the friends he makes and keeps, the charm he exerts in every kind of atmosphere and company. I have been one of his company in a cosmopolitan tavern in New York, and in a private party afterwards. At the first some of the leading aerodynamic and research workers listened to von Kármán talking. At the second he became the centre of a circle of the wives of engineering and science professors. The subjects and the stories, which held the close attention on both occasions, were widely different, but the effect was the same. The man and the occasion are remembered when the names of the companies are forgotten.

The great tragedies of his life have been the losses of his mother and his sister. " His mother was an exceptionally wise and kind lady, adored by all her children, and by all who were fortunate to know her."

It is my great regret I did not meet her, but I was fortunate enough to meet his sister on a number of occasions. She was as capable and as intelligent in her own way as her brother. She took a degree in the history of art at Vienna University and became an enthusiast on Spanish painting and sculpture. Recently von Kármán paid her a charming and moving tribute by dedicating to her memory two Spanish art books, one on Francisco Bayeu, the famous 18th century Spanish mural and fresco artist, and the other on the great sculptors and sculptures of Oviedo and Avila.

This is but an all too brief tribute, but one I have long wished to pay during his lifetime. Theodore von Kármán's students and associates have paid him an outstanding technical tribute. I am not competent to review his technical appreciation, but I would like to end with a quotation from G. V. Lachmann's extremely able paper on The Case for Laminarization, in which he says:

" Defining correctly and accurately these technical requirements is the task of research; prediction of impracticability discourages and delays progress. Once designers and aircraft constructors had clearly appreciated both the potential advantage and the exact technical requirements, many dogmas were disproved in the course of the development of aviation."

Theodore von Kármán has done much to define correctly the technical requirements in the task of research and to sweep away much of the technical pessimism which delays progress.—J. LAURENCE PRITCHARD.

Dr. von Kármán's name is well known to all workers in aerodynamics, but his work covered a very wide range in applied mechanics; consequently this collection of papers, presented as a tribute to his memory, by his former students and co-workers follows the same pattern.

Outside aerodynamics there is " Theory of the Self-Excited Unsymmetrical Gyroscope " (R. Grammel),

"Theoretical Aspects of Rock Breakup in Mining and Construction Work" (T. H. Troller), "The Effect of Size and Shape upon Fatigue Strength" (F. Bollenrath and A. Troost), "Flow and Heat Exchange in Blast Furnace Stoves" (M. Hansen).

For the aeronautical man there is "A Method for Determining the Wing Area and its Aspect Ratio in Aircraft Design" (G. Gabrielli) which is a generalisation of the well-known simple level flight equation, analysing how the main quantities *i.e.* all-up weight, wing area, aspect ratio and power, vary with alterations of the basic data, maximum speed, range or payload; "Some Aspects of Three-Dimensional Flow in Turbo-Machinery" (F. L. Wattendorf)—which is written with special reference to axial-flow compressors; "The Theory of 'Semi-static' Pressure Exchangers" (Lorenzo Poggi) which deals with Lebre's type of pressure exchanger as modified by the author; "Analytical Treatment of Subsonic Flow in a Supersonic Region" (A. Betz) which gives a new method of analysing the change from subsonic to supersonic flow—flow past an infinitely long flat plate is taken as an example; "Systems whose 'Inertial' and 'Gravitational' Masses are not Identical" (F. N. Scheubel) which considers the stability of a descending parachute and the oscillations of a free balloon; and "The Case for Laminarization" (G. V. Lachmann) which treats such matters as roughness, distributed suction transition and Aerodynamic design, with these conclusions (*i*) the benefits resulting from drag reduction demand, for optimum results, a proper choice of cruising height, flight speed, and a power plant tailored to supply the required cruising thrust (*ii*) laminarised aircraft will require some form of take-off assistance or novel methods of take-off (*iii*) the engineering problems involved in flight at high supersonic speed over long distances are probably vastly greater than those involved in laminarisation.

In general, whatever the subject, the serious student can learn much from a study of the methods of attack and analysis. The book is very well printed and illustrated and it should find a place in every college or industrial technical library.—JOHN CASE.

STRENGTH AND RESISTANCE OF METALS. *John M. Lessells. John Wiley and Sons Inc., New York, 1954. 450 pp. Illustrated. 80s.*

This book, like the curate's egg, is good in parts. It has been written by a former member of the staff of the Massachusetts Institute of Technology. It therefore raises great, but unfortunately unrealised, expectations. The book would have been a great deal better if the author had been subjected to stern editorial discipline. Of this work, it can be said, that, *inter alia*, its title is wrong, as is that of one of its many tables; its index is much too restricted and its presentation is sometimes careless—for example, though a number of references are made to the outstanding work of A. A. Griffith, in all but one, the name of this eminent physicist is incorrectly spelt. A competent editor would have eliminated these defects which, although detracting from the merit of the book, are admittedly with one exception, of little magnitude.

To call a book "Strength and Resistance of Metals" which deals, mainly, with some of the properties of a rather limited number of ferrous materials, is surely a considerable misnomer. The title gives promise of a broad survey of a vast subject—there are over 70 metallic elements and rather more than 4,000 commercial alloys. The author, in fact, gives a restricted view of some of the mechanical properties of the metals of a small town scrap merchant's yard—he has looked through his telescope the wrong way.

Dr. Lessells's work contains 450 pages, eleven chapters and, somewhat strangely, some thirty pages of problems, logs, antilogs and trigonometric functions. By far the largest part is devoted to fatigue. In general, the author's treatment of what is seemingly, his principal interest, is adequate and, more often than not, better than this. As is entirely right, he surveys the past. He refers appreciatively to papers by more than 300 authors. He has, however, a quite overwhelming predilection for those of such Old Masters as Gough, Moore, and Timoshenko. Templin, that brilliant contemporary experimenter gets but a single mention, while Forrest, Forsyth, Wilson, Zambrow and Fontana, each of whom has made at least one post *Second* World War worthwhile contribution to our knowledge, are unmentioned.

Three major technical criticisms can be fairly levelled at Dr. Lessells's work. He totally fails to emphasise adequately how vast can be the scatter in fatigue results. He does not point out, how, as originally stated, utterly untrustworthy was and, in fact, is the Cumulative Damage Rule. He neglects to tell the reader to what absurdities well conducted experiments can reduce the sensitivity value "*q*." His book, though not without merit, because of the materials with which it deals, will be of little interest to the aeronautical engineer. Such a man can undoubtedly spend four pounds (which is the price of this book in this country) more advantageously.—P. L. TEED.

TITANIUM. *A. D. McQuillan and M. K. McQuillan. Butterworths, 1956. 466 pp. Illustrated. Price 56s.*

In 1789, the Reverend William Gregor, by implication rather than by isolation, discovered titanium. In the century and a half following this event, the metal was severely neglected except by the few. In the past 10 to 15 years, however, it has attracted the attention of the many. With some, interest has been due to scientific stimulation. With others, possible technical applications have been the *raison d'être*, while with yet others the hope that it might provide a means of acquiring wealth has been the activating principle.

By no means have all the foregoing kept their interest to themselves. Some in each class have committed their views to paper. In the last decade this has resulted in over a thousand publications having titanium as their subject. Some of these are in the form of often rather poorly produced scientific papers, some are technical notes and finally there are some which are frank, or perhaps not so frank, sales propaganda—these last, curiously enough, are invariably on most highly glazed sheets—smooth words on smooth paper.

At the present time, the literature of titanium can be described, in the main, as being voluminous rather than meritorious. There are, however, several exceptions to this all too sweeping generalisation and the work under consideration is very definitely one of them. In a book of under 500 pages containing some 14 chapters and 200 illustrations the McQuillans have reviewed, in a most satisfactory manner, the very considerable existing knowledge with regard to the production of titanium, its chemical qualities and the physical ones, both of the metal and of very many of its all too many alloys. In addition, they give much useful information with regard to many of the processes employed in fabrication. Admittedly the authors have a greater metallurgical than engineering outlook but, both to the metallurgist and to the engineer, this book will certainly be extremely informative.—P. L. TEED.

EARTH SATELLITE—THE NEW SATELLITE PROJECTS EXPLAINED. *Patrick Moore. Eyre and Spottiswoode, London, 1955. 128 pp. 15s.*

The official announcement from the White House last July that the Americans intend to establish small instrument-carrying satellite rockets in orbits just beyond the atmosphere was swiftly followed by another, to the effect that the Russians intend to do likewise. In both cases, the intended time-scale is apparently only a matter of some two or three years—a fact which suggests that considerable progress with large rockets, beyond the V.2, has been made on both sides of the Iron Curtain. If such technical achievements manifest themselves as scientific research projects of this nature, rather than as inter-continental ballistic missiles, the world may well rest content, although in practice no doubt we shall have both, just as we have jet air liners and strategic bombers.

In spite of a recent pronouncement by the new Astronomer Royal the instinct of the man-in-the-street tells him that all this is the real beginning of space-flight, and he is quite right. Newspaper reports and articles, particularly since the satellite announcements, testify to his considerable interest in such subjects, and the little book now under review should go a long way towards satisfying this. The reader, incidentally, may be amused to find in Mr. Moore's book a quotation from the retiring Astronomer Royal (Sir Harold Spencer Jones): "To conquer space would be an achievement surpassing anything that man has yet accomplished; the greater therefore is the challenge. There are those who are prepared to accept the challenge, and who can say that they will not succeed? . . . Their faith is not mere idle fancy, but there are solid grounds for believing that sooner or later success will be theirs."

The style of the book is entirely popular, but it is only rarely inaccurate, and even then not in any way detracting seriously from its intended purpose. Although short, it succeeds in covering a much wider field than its title might suggest, for it has something to say about rocket history, high altitude research, space-flight, and astronomy generally.

Its author is well qualified to write such a book, for he is a leading amateur astronomer, recognised as an authority on the Moon and planets, and is a Council member of the British Interplanetary Society. Like his other books on astronomical subjects, it may confidently be recommended to the general reader.—A. V. CLEAVER.

THEORY OF MACHINES. *W. G. Green. Blackie, Glasgow. 1034 pp. Diagrams. 40s. net.*

The author in the preface to this book says that his main purpose was to meet the needs of students preparing for the external degree examinations of the University of London, College Associateship and Higher National Certificate examinations, and for the examinations of the professional Institutions. The outcome is a monumental discursive treatise. The first two chapters occupying 134 pages are concerned with fundamental principles of particle and rigid dynamics. In all there are 17 chapters. To quote from the preface: "Throughout the whole of the book the aim has been to preserve a logical sequence and this has largely dictated its size and content. Chapters XII and XV on Belt Friction and Cams were developed in this way, without reference to existing theory and the treatment is substantially new. This applies also, but to a lesser extent, to the chapters on Governors and Toothed Gearing, while the inclusion of a chapter on Film Lubrication needs little comment as this subject plays an important part in the dynamics of machinery."

The book contains a large number of worked examples, for the most part taken from the External degree examinations of London University, and from those of the professional Institutions. The text is well printed and there are numerous clearly drawn diagrams. There is also a good index.

The volume is a veritable storehouse of useful information on mechanisms and practical applications of them and fully justifies the purpose and publication of the work.

The author somewhat surprisingly seems to avoid committing himself on the concept of inertia force as a real force. Instead he makes use of the artificial and academic notion of "effective force," although in this connection he does refer to inertia effects. Newton in his *Principia*, Def. 3, Book 1, discussing *vis inertiae*, remarks " . . . . it is resistance in so far as the body, for maintaining its present state, withstands the force impressed." "This terminology," says Minchin*, "has been wholly ignored by English writers, and, as a result, the fact that a body exerts a *kick* . . . against any agent which acts on it . . . has been lost sight of. The student must carefully observe that the force of inertia of a moving particle is not a force acting *on* the particle but one exerted *by* it on some agent, direct or indirect.

"D'Alembert, in enunciating the kinetic principle known by his name, speaks of the force of inertia as *effective force*, and this deviation from Newton's definition and the physical idea contained in it has been followed by English writers. Most, if not all, the modern French writers have adhered to Newton's definition."

The weakest part of the book, in the reviewer's opinion is the treatment of the very important problem of the whirling of shafts. In the light of the author's clear description of Coriolis force on p. 70, it is curious that in the one phenomenon in which the Coriolis effect is of cardinal importance, the author neglects this effect, and thus once again promulgates an indefensible fallacy affecting a basic concept in the theory of machines, namely, the concept concerning the physics of shaft revolution. In this fallacy,† apparently first given respectable parentage by the renowned Rankine in 1869, it is assumed that a rotating shaft normally vibrates in one plane, which plane revolves with the imposed rotation. It is this fallacy, too, which leads to the quite incorrect result that the frequency of transverse vibration of a balanced symmetrical shaft is a function of the speed of rotation and that whirling takes place when this frequency becomes zero (*see* for example p. 942). Dunkerley's empirical rule regarding an approximation to the fundamental frequency of vibration of a system of loads is demonstrated for the trivial case in longitudinal vibration in which all the loads are concentrated at one point (*see* p. 892). In the author's treatment of the transverse vibration of a number of loads on a beam by the method of strain energy the assumption is made that the amplitudes of vibration at the loads will be proportional to the static deflections of the loads at those points. This, of course, is an artifice for deriving an approximate value of the fundamental frequency. Mention of this would avoid misunderstanding, since the process is described as more accurate than, presumably, the Dunkerley approximation which precedes it.

The writing of a book like this is a Herculean task and the service rendered by the author will be appreciated by a wide circle of readers.—J. MORRIS.

**Kinematics.* The Clarendon Press. 1882.

†*See e.g.*, The Dynamics of Shaft Revolution. *Mechanical World.* 22 June 1951.

ADVANCED CALCULUS. *Louis Brand. John Wiley and Sons Inc., New York, 1955. 574 pp. Illustrated. 68s.*

The scope of this book is set out by the author in his preface as "a course in analysis dealing essentially with functions of a real variable". To these eleven chapters on the real variable is added one on functions of a complex variable as Dr. Brand feels that certain parts of real variable theory can be fully explained only by considering the complex variable.

Chapters are devoted successively to sequencies and series, functions of one variable and of several variables, viscous, definite, improper, line and multiple integrals, uniform convergence, then the complex variable and, finally, to Fourier series. The opening chapter which sketches the structure of the system of real and complex numbers may, Dr. Brand says, "be provisionally omitted and referred to as occasion arises". There are four Appendices (each of 2 or 3 pages) on Cluster point, Difference equations and the Difference Calculus, and Dimensional checks.

In a book of 552 pages (with another 22 devoted to answers to problems and a full index) some important subjects had to be omitted. Differential equations and the summation of divergent series are only casually mentioned. Also Libesque integrals, regarded as part of the theory of functions are outside the scope of this book on "Classical Analysis".

The final article on each chapter does give a brief summary of its content (although expressly stated in the "Contents" for chapters 3 and 4) Full cross references are given with a clear style of numbering applied to theorems, examples and problems. This layout, with a good index, enables the reader to find his way almost easily.

Yet it is difficult to see what type of English student could profit by reading this book. It is a curious mixture of more sophisticated method with the more elementary approach. There is much valuable material. The treatment of uniform convergence is good and there are many useful illustrations in the chapter on multiple integrals. The use of complex integration in computing real integrals justified the introduction of the complex variable chapter. But the method of introducing Scalar and Vector products is just the reverse of what, surely, should be aimed at.

To the academic student who is familiar with the treatment of these subjects in comparable English text-books a reading of chapters in this "Advanced Calculus" should give a glimpse of advanced techniques at a much earlier stage than usual. This new insight, together with a perusal of many interesting but unusual "treatments" (and a working through the valuable examples and problems) should provide a worthwhile mathematical discipline. Certainly no other book has this material approached quite in this way and linked together as here. Those acquainted with Brand's "Vectorial Mechanics" may expect this.—A. J. HATLEY.

THERMODYNAMICS. *J. F. Lee and F. W. Sears. Addison-Wesley, Cambridge, Massachusetts, 1955. 536 pp. Diagrams. $7.50.*

This book is yet another in a long line of American text-books on this subject which proclaim the doctrine that fundamental principles should be taught with little or no reference to practical applications. In the reviewer's opinion, this is an extreme case of obedience to this particular fetish.

The first seven chapters (some 200 pages) are devoted to consideration of the First and Second Laws of Thermodynamics and their consequences. There is more than a little danger that the length of these chapters will lead to confusion rather than to the clarity which their detail is intended to produce. A complete list of the symbols used throughout the book, together with their meanings, might help to clarify this section.

The following chapters on fluid flow, heat transfer and mixtures are presented much more clearly, but even here there is a regrettable tendency to make difficulties and fail to resolve them. It seems, for instance, rather unnecessary to produce complex equations for heat flow by conduction, the solutions to which "can be quite complicated and beyond the scope of this book."

Chapters 11, 12 and 13 are concerned with power and refrigeration cycles, but the authors consider these with only passing reference to practical considerations. It is surely undesirable to imply that the modern compression-ignition engine "may be construed to operate on the air standard Diesel cycle," *i.e.* with constant pressure heat addition.

Almost as an afterthought, in Chapter 14 an attempt is made to deal in about thirty pages with the "Thermodynamics of Reactive Systems"—a hopeless task.

A useful range of thermodynamic data, together with a section of rather doubtful value on systems of units, is presented in a series of appendices.

This is not a book which the reviewer could recommend to undergraduate students, and it has few of the attributes required of a reference book.—H. BILLETT.

THERMODYNAMICS AND PHYSICS OF MATTER. *Edited by F. R. Rossini. Oxford University Press, London, 1955. 812 pp. 100s.*

The purpose of this volume is to present the basic principles of thermodynamics and of the physics of matter to scientists primarily concerned with high speed aerodynamics and with jet propulsion. It is divided into ten articles which cover a wide range of topics, the standard being in most cases well above that reached in an honours physics course. While the topics themselves are not specifically related to aerodynamics problems—these being reserved for further volumes in the series—they certainly provide a useful background to these problems.

Two of the articles are devoted to general thermodynamics, one dealing with thermodynamic laws and their applications, the other with the thermodynamics of irreversible processes. There is a useful survey of the properties of solids, including those of metals and alloys, a discussion of the modern theory of liquids and of phenomena associated with condensation under critical conditions. The majority of the articles deal with the physics of gases. A comprehensive account is given of molecular bonding and of collision theory for molecules; kinetic theory is considered in fair detail, including transport phenomena at normal and at low pressures. Of particular interest is the article dealing with relaxation phenomena in gases; the question of the transfer of various forms of energy between molecules during collisions is of importance in propagation processes in general and in the special case of the propagation of shock waves. The treatment includes an admirable discussion of the absorption and dispersion of sound waves in gases both from the theoretical and the experimental angle. Another section of special importance to those interested in the thermodynamic properties of gases is that devoted to the discussion of equations of state for real gases and gas mixtures. This contains a full numerical discussion of empirical equations of state, of virial coefficients, of thermodynamic function and heat capacities.

The articles are well written and well documented and the general production leaves little to be desired. The volume is strongly recommended both as a text-book and as a work of reference.—M. BLACKMAN.

ULTRASONIC ENGINEERING. *A. E. Crawford. Butterworths Scientific Publications, London, 1955. Illustrated. 344 pp. 45s.*

The jacket and preface are full of promise ". . . the subject of ultrasonics . . . has entered the province of the engineer for whom this book has been written. The thorough knowledge of the underlying basic theory which the book supplies is essential to the successful application of the method. . . ."

This promise is shattered on page *one* where " the reader is referred to any modern textbook on acoustics for a detailed account of the concept of wave motion. Briefly . . . ", is followed by a naive flirtation with the waves, demanding an infinite depth of appreciation from those who don't know the waves already. There are plenty of formulae, gracefully displayed: manna from heaven indeed, unadulterated by details of their mundane origin from the First Principles. We are given many references to seek out their beginnings in the literature: the most beloved of all, the Speed of Sound, comes foremost and perhaps has Teutonic strains since we are to search in *" Der Ultrasehall "* for details.

The first part of the book—on discarding the chaff—is a collection of denuded facts. Indeed, " . . . the object of this book is to collect and correlate the mass of data available. . . ." The general pattern of the book—Theory, Generation, Application—is really the only sensible one, but the weakly character of the early pages reappears from time to time. The jet generators for example have a fine photogenic physique, described with the aid of good diagrams to the nearest 0·0001 in. for critical parts, but their mode of operation is crudely (and sometimes incorrectly) described. The high pressure jet of the Hartmann whistle contracts to pass through a single point, the pathlines crossing over at said point to reappear on the other side of the jet (diagram to make this clear). This point, one is led to believe is " a point of instability "—no doubt the ultrasonic whistle is related to frustrated Equations of Continuity!

On the whole the more practical chapters are of much sounder stuff, packed with information and straining the foundations provided. The field covered is enormous and there will be much of interest to everybody and scores of references are given. Whole chapters are devoted to Precipitation and Agglomeration, Emulsification and Dispersion, Chemical Applications (introducing sonochemiluminescence!), Metallurgical Applications, Coating of metals, and Biological and Medical Applications. The greatest value of the book, I think, is the illustration of how new techniques develop and find very widespread application in laboratories and plant of widely different nature. This variety of applications makes it difficult for a single author to elucidate them clearly enough to convey the significance of all the processes involved—on the whole these are done reasonably well but patches went over my head. (The significance of " the reduction of the sodium salt of 2:6 dichlorophenal in aqueous solution by ultrasonically produced nitric acid reaches its maximum rate at about 166 erg/cm.^{3} . . ." will not strike many engineers for whom this book is written. But all engineers will understand the import of the German claim that the maturing time of wines and spirits can be reduced to days).

Of course, I fully realise that book reviewing has much in common with that of gramophone records—it depends on one's taste and outlook. My appetite was whetted by the opening gambit, and I found that I went hungry for a long part of the way. But perhaps I should have thought of Heaviside's remark. close to the hearts of many engineers " Shall I refuse my dinner because I do not fully understand the process of digestion?"—ALAN POWELL.

TURBOBLOWERS. *A. J. Stepanoff. John Wiley & Sons Inc., New York, 1955. 377 pp. Illustrated. 64s.*

This book aims to present the state of the turbocompressor art in U.S.A. and abroad. It is well put together and shows that the writer has come under European and American influence. For instance, the author follows Buckingham's methods of dimensional analysis. whereas English workers follow Capon and Brooke. while the European influence is shown as well in the relative circulation in the theory of the centrifugal impeller. The first chapter seems unnecessary, as the selected topics arise naturally in the text.

Emphasis is properly on the dynamic nature of these machines and the velocity triangle diagrams are cleverly drawn. The art of design of centrifugal compressors is dealt with, but not so well as methods of correlation and analysis of results. Hydraulic performance of blowers is well covered and the author introduces his master diagram and gives examples of its use. When the reader has got used to the non-dimensionals employed, the use of this chart does govern the design of centrifugal blowers without inlet guide vanes.

The very important case of radially bladed centrifugal blower is not specially considered, and the problems of very high duty compressors hardly mentioned. On the other hand centrifugal and axial flow fans are well covered. The chapters on Thermodynamics and compression with cooling are very well written and numerically exemplified. The author's treatment of high pressure multi-stage axial flow compressors is well worth reading and gives a good account of velocity triangles suitable for such designs. British National Gas Turbine Establishment design curves and formulae are Americanised and taken over into the text. It is felt that the author would have done better to stick to British N.G.T.E. usage and symbols. There is much missing from this portion of the book; to mention only a few—surge line difficulties with high pressure blowers, effect of bleed and stator variables, blade stress and so on, and this is perhaps a reflection of the untidy state of high pressure axial compressor art.

Notwithstanding its limitations, the book will find a place on the shelves of most English speaking mechanical engineers with an interest in compressors and pumps.—W. T. HOWELL.

AIR POWER. *Asher Lee. Duckworth, London, 1955. 200 pp. 15s.*

This is a remarkable book. In two hundred pages Mr. Lee has dealt with eleven major problems of air power. Compression, ruthless and effective, has made this possible. To many the result will be satisfying, in this age of speed and hurry. Others will be left with a feeling of regret that so little space was devoted to dealing with matters of such great importance. They may also suffer from a form of mental indigestion.

The author's approach to the problem is didactic and emphatic, and some of the sweeping statements he makes will not bear close examination. Nevertheless he treats this vast subject with very great skill and knowledge, the result of much study and research. As a text-book for air staff colleges, and indeed for all types of military

students it will be invaluable, provided that care is used to verify some of Mr. Lee's hypotheses.

One of the most important chapters deals with air intelligence, which is separated, perhaps wisely, from that on air reconnaissance, although this leads to some repetition. In the result, however, a very complete picture is drawn of the need to base all forms of operation on the products of air reconnaissance and other types of intelligence material.

The chapters on "Combining the Services" and "The Future" are interesting and controversial. Many will not agree with the author's views, but, looking towards what may develop in the next twenty years, it is hard to see where he is wholly wrong and his imaginative treatment of these matters is quite fascinating.

His final conclusion that Germany remains perhaps the greatest danger to world peace will find an echo in the hearts of most Frenchmen, as well as in the minds of those of us who have fought in two world wars.—P. B. JOUBERT.

JANE'S ALL THE WORLD'S AIRCRAFT 1955-56. *Edited by Leonard Bridgman. Jane's all the World's Aircraft Publishing Co. Ltd., London, 1955. 409 pp. Illustrated. £4 4s. 0d.*

The usual purpose of a review is to indicate whether or not a book is worth buying, but this does not apply with "Jane's" because the only thing that could stop anyone interested in aircraft from buying it is lack of four guineas. It only remains to say that the 1955-56 edition is out, it is as good as ever, there are 30 more pages of text and 15 more of advertisements compared with last year, and non-scheduled airline operators are included for the first time. The layout is the same as it has been for a number of years, which is as good as saying that it cannot be improved.

DEUTSCHE LUFTFAHRTGESETZEBUNG (GERMAN AIR REGULATIONS). *Second Edition. Alfred Wegerdt. Pohl, Munich, 1955. 277 pp. 16.80 DM. (In German).*

The Nine Power Conference in London in October 1954 and the Paris Agreement later in the same month gave the Government of Western Germany the responsibility for German Civil Aviation, whereas up till then the Forces of Occupation had been the supreme authority. Because of this change over, the second edition of this book has been completely revised, and as German Civil Aviation gets into its stride there will be a constant flow of new regulations which the book will help to identify. The Introduction explains where changes and additions to the regulations may be expected and the last chapter contains the new agreements made at the London and Paris Conferences.

AVIATION FACTS AND FIGURES: 1955 EDITION. *R. Modley and T. J. Cawley (Compilers) for Aircraft Industries Association of America. Lincoln Press. 103 pp. $1.00.*

When the 1953 edition of this work was reviewed in the JOURNAL of February 1954 the reviewer deplored the fact (from a purely selfish viewpoint) that the excellent collection of figures applied almost entirely to American industry (naturally) but added that there was a chapter dealing with Foreign Aviation Data. This time there is no such chapter. Significant alterations are: a chapter on Guided Missiles and a separate chapter on Helicopters.

METEORS. *Edited by T. R. Kaiser. Pergamon Press, London and New York, 1955. 204 pp. Illustrated. 55s.*

This volume is a special supplement to the *Journal of Atmospheric and Terrestrial Physics* and contains papers presented at a symposium on meteor physics held at the Jodrell Bank Experimental Station in July 1954. The contributors are active research workers and represent all of the countries in which work of major importance is in progress in the fields of meteor astronomy and physics. While the main emphasis is on physical problems of meteors and the upper atmosphere, a number of papers on important astronomical questions are included.

WORLD AIRLINE RECORD. *5th Edition. Edited and published by R. R. Roadcap and Associates, Chicago, 1955. 500 pp. Illustrated. 125s.*

This is not the sort of book which one can review in the accepted sense of the word. It is another of those volumes that prove their worth with time and use and at 125s. there is quite a lot of worth to prove.

There is a mass of information about every airline one can think of and many that one cannot. Airlines that have dropped out of business or have been "absorbed" are listed in the front of the book and a reference given to the previous edition in which they were described.

It is not, of course, the sort of book one reads. It is the type that should be in every collection of books that pretends to solve aeronautical inquiries.

TECHNICAL AERODYNAMICS. *Karl D. Wood. Third Edition. Published by the author and distributed by Ulrich's Book Store, Ann Arbor, Michigan, 1955. 384 pp. Illustrated. 60s.*

This, the Third Edition of a book too well-known to need a full review, has been printed by photo-litho from typescript. In this it now resembles its companion *Airplane Design*, but one cannot say that this method of producing the book is an improvement, except in so far as it may have helped to keep the price down. However, the material is there, brought right up to date since the Second Edition of 1947. The object of this book is "to provide a course of study for the engineering student (or a refresher course for the practising engineer) which will help fit him to make the performance, stability and aerodynamic design calculations of current importance in the aircraft manufacturing industry" and, as we know from previous editions, this object is well achieved.

SUPERSONIC AIRCRAFT. *Roy Cross. Macdonald, London. 1955. 62 pp. Illustrated. 6s. 6d.*

This book should have a ready sale because it summarises the answers to so many questions that the fourteen plus lad has an awkward habit of asking. It explains what happens at Mach 1 and tries to strike a happy medium of all the explanations of the sonic bang. It gives a chronological list of the early "barrier-crashings" and, strangely enough, credits a May 1947 Soviet claim, "probably in a dive." The illustrations are good and altogether it would make an excellent and appreciated present for the age between Dinky toys and ties.

SIX GREAT AVIATORS. *John Pudney. Hamish Hamilton, London, 1955. 220 pp. 8 photographs. 10s. 6d.*

This book is one of a series of "Six Great" (Englishmen, Englishwomen, Inventors and so forth). John Pudney has a considerable reputation as a writer on airmen and these potted biographies will suit the modern reader who likes his material in "digest" form. The biographies included are of A. V. Roe, Alcock and Brown, Kingsford-Smith, Lindbergh, Saint-Exupéry and Neville Duke.

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**Items marked thus are for reference use only.*

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576 Thermal Stresses and Deformations in Beams — S. Levy
577 Investigation of the Temperature Distribution and Thermal Stresses in a Hypersonic Wing Structure — M. A. Goldberg
578 Approximate Procedures for Transient Thermal Stresses in Missile Structures — B. E. Gatewood
579 Influence of Aerodynamic Heating on the Effective Torsional Stiffness of Thin Wings — B. Budiansky and J. Mayers
580 The Display of Hail Echoes on 5·5 cm. Weather Mapping Radar — H. T. Harrison
581 Minimal Flight Paths from Forecasts of the Joint Numerical Weather Prediction Unit — F. Lewis
582 Implications of Convective Cloud Observations with Regard to Flight Operations with Airborne Radar — L. J. Battan
583 All Weather Flight Concern of the Pilot and Weather Forecaster — J. K. Thompson
584 The Turbine Propeller Combination in the Air Force — Lt. Col. R. J. Wellman
585 Effect of Rib Flexibility on the Vibration Modes of a Delta Wing Aircraft — W. D. Kroll
586 Structural Behavior of Seaplane Hull Bottom Plating — J. W. Cox
587 Delay of the Stall by Suction Through Distributed Perforations — A. Raspet *et al.*
588 Demonstration of Reliability in Liquid Propellant Rocket Engines — A. G. Thatcher and H. A. Barton
589 Improved On-Off Missile Stabilization — R. W. Bass
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600 Investigation of Whirl Test Methods for Inducing Flight Fatigue Loads in Helicopter Rotors — C. F. Rice
601 Zero-Lift-Drag Characteristics of Wing - Body Combinations at Transonic Speeds — R. T. Whitcomb
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603 Optimalizing Cruise Control for Turbojet Aircraft—Part I; Programmed Cruise Control for Turbojet Aircraft—Part II — W. B. Bryant and H. L. Pastan; M. A. Hoffman and A. J. Navoy
604 Transient Stresses in Airfoils Subjected to Blast Loading — F. J. Marshall and H. F. Ludloff
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606 Safety and Economic Aspects of Flight Simulators — A. F. Bonnalie

Reports

AERODYNAMICS

Boundary Layer

See Wings and Aerofoils

Compressible Flow

An experimental study of one-dimensional refraction of a rarefaction wave at a contact surface. I. J. Billington. UTIA Report No. 32 (*June* 1955).

Experimental results are presented on the form of the rarefaction wave generated by the bursting diaphragm in a shock tube. It is shown that this wave has a higher pressure and lower velocity behind it than the wave predicted by ideal shock tube theory and that it has a different form from that of the ideal wave. This rarefaction wave is utilised as the incident wave for a study of the refraction of a rarefaction wave at a contact surface.—(1.2.3).

Lois de la réflexion des ondes de choc dans les écoulements plans non stationnaires. H. Cabannes. O.N.E.R.A. Pub. 80 (1955).—(1.2.3.2).

Internal Flow

Theoretical and experimental analysis of low-drag supersonic inlets having a circular cross section and a central body at Mach numbers of 3·30, 2·75, *and* 2·45. *A. Ferri and L. M. Nucci. N.A.C.A. Report* 1189 (1954).

A discussion of inlets having a circular cross section and a central body, designed for high Mach numbers, has been made. The optimum relationship between external and internal supersonic compression has been discussed with respect to the external drag and the maximum pressure recovery. Practical design criteria have been given and tests of inlet configurations designed from these criteria have been presented for Mach numbers of 3·30, 2·75, and 2·45 and for corresponding Reynolds numbers ranging from $3{\cdot}5\times10^6$ to $3{\cdot}0\times10^6$. Values of maximum pressure recovery and shadowgraphs for different combinations of central body and cowling shape and for different positions for central body relative to cowling have been given.—(1.5.1).

Wings and Aerofoils

Measurements of the effect of trailing-edge thickness on the zero-lift drag of thin low-aspect-ratio wings. J. D. Morrow. N.A.C.A. T.N. 3550 (*November* 1955).

Results of an exploratory free-flight investigation at zero lift of several rocket-powered drag research models having tapered 4 per cent. thick wings are presented for a Mach number range of 0·7 to 1·6. Wings having an aspect ratio of 3·11 and trailing edge thicknesses equal to 0, 1/3 maximum thickness, 2/3 maximum thickness and the maximum thickness were tested. The sections were identical circular arcs back to the 40 per cent. chord station. The remainder of the section was formed by drawing a tangent from the trailing edges of various thicknesses to the extended circular arc.—(1.10.2.2 × 1.1.3.4).

Helicopter Aerodynamics

Helicopter instrument flight and precision maneuvers as affected by changes in damping in roll, pitch, and yaw. J. B. Whitten, J. P. Reeder, and A. D. Crim. N.A.C.A. T.N. 3537 (*November* 1955).

The damping in roll, pitch, and yaw of a single rotor helicopter was varied by means of electronic components, and these variations were evaluated by performing instrument approaches and other precision manoeuvres. Increased damping in roll was found to be particularly beneficial, whereas corresponding changes in yaw and pitch were less effective. Some operational aspects of helicopter instrument approaches are also included in the discussion.—(1.11.2).

Testing and Instruments

An experimental investigation of flow separation in a nozzle at high Mach numbers and low density. N. B. Tucker. UTIA Report No. 33 (*August* 1955).

Experimental evidence of a stable form of flow separation was obtained in a two-dimensional wedge nozzle with a 1 in. throat radius at area ratio Mach numbers above 4 in the UTIA 5 in. × 5 in. supersonic wind tunnel. The separation occurred without any abrupt change in static pressure gradient and without a shock wave being associated with the phenomenon. It was found possible to delay separation by approximately 1·9 Mach numbers by the use of distributed surface roughness in the supersonic portion of the nozzle.—(1.12.1).

Papers presented at the sixth meeting of the wind tunnel and model testing panel. AGARD Memorandum 17/*P*7.

The papers include: calibration of test sections; requirements for uniformity of flow; calibration of the flow; flow direction measurements; scale effects; methods of determination; identification and starting of the transition; transonic wind tunnel development; flow establishment; heat transfer; GALCIT hypersonic research; ultra-high temperature; improvement of the study; design and operating techniques; the vertical spinning tunnel.—(1.12.1).

Development of turbulence-measuring equipment. L. S. G. Kovásznay. N.A.C.A. Report 1209 (1954).

Hot wire turbulence measuring equipment has been developed to meet the more stringent requirements involved in the measurement of fluctuations in flow parameters at supersonic velocities. The higher mean speed necessitates the resolution of higher frequency components than at low speed, and the relatively low turbulence level present at supersonic speed makes necessary an improved noise level for the equipment. The equipment covers the frequency range from 2 to 70,000 cycles per second. The equipment is adaptable to all-purpose turbulence work with improved utility and accuracy over that of older types of equipment. Sample measurements are given to demonstrate the performance.—(1.12.6).

AIRPORTS

A theoretical analysis of the field of a random noise source above an infinite plane. P. A. Franken. N.A.C.A. T.N. 3557 (*November* 1955).

The sound field about a random noise source above a plane as measured by a receiver with finite band width is studied theoretically. For simplicity, only the far field is considered. The special case of a perfectly reflecting plane is discussed first and the analysis is then extended to include the case of a plane of arbitrary impedance.—(6.4).

MATERIALS

*The development of a wire testing machine. I. G. Scott. A.R.L. Note SM.*216 (*July* 1955).

The development of a machine for the testing of the fine wire used in strain gauge manufacture is described. In the course of the work, values for Young's modulus, ultimate load, maximum elongation, and gauge factor were obtained for samples from several different spools of soft and hard drawn "Advance" wire.—(21.6.2).

Metallography of aluminum and its alloys: use of electrolytic polishing. P. A. Jacquet. N.A.C.A. T.M. 1384 (*November* 1955).

Recent methods are described for electro-polishing aluminium and aluminium alloys. Numerous references are included of electrolytic micrographic investigations carried out during the period 1948 to 1952. A detailed description of a commercial electrolytic polishing unit, suitable for micrographic examination of aluminium and its alloys, is included. —(21.1).

NOTE.—*The figures in parenthesis at the end of each Summary are for office use only.*

Failure of materials under combined repeated stresses with superimposed static stresses. G. Sines. N.A.C.A. T.N. 3495 (*November* 1955).

Experiments on biaxial alternating stresses and simple combinations of static stress with alternating stress are reviewed. A general criterion for the effect of static stress on the permissible amplitude of alternating stress is proposed and compared with results of tests performed under more complex stress states.—(21.0).

POWER PLANTS

An accurate calibration of a Derwent 8 *gas turbine. R. V. Pavia. A.R.L. Note ME.*202 (*August* 1955).

Measurements of thrust have been made on a Derwent 8 gas turbine. In the tests, particular care was taken with the test bed instrumentation.—(27.1).

SCIENCE—GENERAL

Mise en équations et résolution des réseaux électriques en régime transitoire par la méthode tensorielle. A. Kaufmann. Pub. Sc. and Tech. N.T. 56 (1955).—(32.2.1).

STRUCTURES

Theory and Analysis

Deflection measurements on a 45° *swept and tapered rectangular tube. G. L. Belcher. A.R.L. Report SM.*228 (*June* 1955).

As part of a programme of stress and deflection analysis of swept tubes, a tube of rectangular cross section, tapered in both plan form and thickness and having 45° of sweep at the leading edge, was loaded by a concentrated load at each of eight points in turn, and deflections were measured at eighteen positions for each load position.—(33.2.4.11.3).

*On the solution of problems of dynamic plane elasticity. J. R. M. Radok. A.R.L. Report SM.*230 (*July* 1955).

Introduction of the complex variable approach into the study of the dynamic equations of plane elasticity leads to a simplification of the statement as well as the process of solving problems dealing with surface waves. The relevant solution of the differential equations is shown to be expressible in terms of two analytic functions, corresponding to the two types of waves occurring in elastic media. The stress and displacement components are easily expressed in terms of these functions leading to a reduction of the boundary value problems to problems of complex function theory.—(33.2.1).

Universal column formula for load at which yielding starts. L. H. Donnell and V. C. Tsien. N.A.C.A. T.N. 3415 (*Oct.* 1955).

An analysis is presented of the load at which yielding first occurs in actual columns, taking adequately into account all the factors which have an important effect upon this load. The results are expressed as a formula or chart applicable to all cases.—(33.2.4.2.1).

Analysis of stresses in the plastic range around a circular hole in a plate subjected to uniaxial tension. B. Budiansky and R. J. Videnšek. N.A.C.A. T.N. 3542 (*Oct.* 1955).

An approximate theoretical solution is presented for the stresses in the plastic range around a circular hole in an infinite sheet subjected to uniaxial tension. The solution is based on the simple deformation theory of plasticity and is found by application of a variational principle in conjunction with the Rayleigh-Ritz procedure and the use of a high-speed computing machine (SEAC). Numerical results are obtained for four different materials, which are characterised by four distinct uniaxial stress-strain curves. The results for stress concentration factor in the plastic range are compared with those obtained from a formula due to Stowell.—(33.2.4.5.1).

Comparison between theoretical and experimental stresses in circular semimonocoque cylinders with rectangular cutouts. H. G. McComb, Jr. and E. F. Low, Jr. N.A.C.A. T.N. 3544 (*Oct.* 1955).

Comparisons are made between a theory for calculating stresses about rectangular cut-outs in circular cylinders of semi-monocoque construction published in N.A.C.A. T.N. 3200 and previously published N.A.C.A. experimental data. The comparisons include stresses in the stringers and shear stresses in the centre of the shear panels in the neighbourhood of the cut-out.—(33.2.4.3.0).

Testing

*A simple resistance comparator. I. G. Scott. A.R.L. Note SM.*220 (*October* 1955).

A simple comparator, for use in the resistance batching of electrical resistance strain gauges, is described. Resistances in the range 170 to 220 ohms can be measured to within 0·5 ohms.—(33.3.1).

THERMODYNAMICS

Thermodynamic Properties

Flame propagation limits of propane and n*-pentane in oxides of nitrogen. Riley O. Miller. N.A.C.A., T.N.* 3520 (*August* 1955).

Flame propagation limits of propane and *n*-pentane in oxides of nitrogen were obtained at sub-atmospheric pressures in a 2-inch-diameter by 48-inch-length tube. Three oxidants were investigated, namely, nitric oxide NO, nitrogen tetroxide N_2O_4, and a nearly equimolar mixture of these two oxides—(34.1.1).

A polar-coordinate survey method for determining jet-engine combustion-chamber performance. R. Friedman and E. R. Carlson. N.A.C.A. T.N. 3566 (*September* 1955).

An automatic polar co-ordinate traversing system is described that sweeps a probe through a quarter-annular exhaust duct circumferentially at selected radial positions. With a single combined pressure and temperature probe, temperature and pressure are recorded simultaneously as a function of probe position. The use of these data in calculating temperature and flow profiles, combustion efficiency, and pressure loss is shown.—(34.1.1).

Heat Transfer

Response of homogeneous and two-material laminated cylinders to sinusoidal environmental temperature change, with applications to hot-wire anemometry and thermocouple pyrometry. H. H. Lowell and N. Patton. N.A.C.A. T.N. 3514 (*September* 1955).

A theoretical investigation of the response of homogeneous and two-material laminated, infinite cylinders to sinusoidal environmental temperature and/or small heat-transfer coefficient changes was made. Generalised results are given for the cylinder consisting of a shell of high thermal conductivity and a core of low conductivity. The behaviour of a number of specific platinum-fused-quartz "wires" of varying construction and diameter exposed to a representative air stream is indicated.—(34.3.0 × 34.3.2.4).

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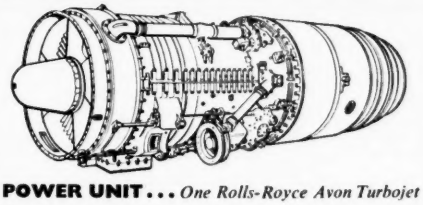

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